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PROJECT TECHNICAL REPORT

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STEADY-STATE SIMULATION PROGRAM FOR  
ATTITUDE CONTROL PROPULSION SYSTEMS

MSC/TRW TASK E-99

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NAS 9-12330

MARCH 1973

Prepared for  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
JOHNSON SPACE CENTER  
HOUSTON, TEXAS

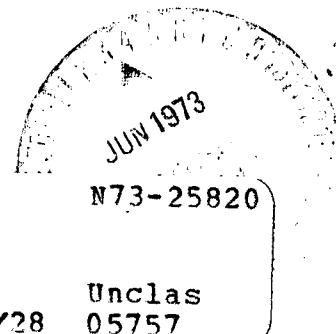
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## 1.0 SCOPE

This report presents the formulation and the engineering equations employed in the Steady-State Attitude Control Propulsion System (SSACPS) simulation program. The initial development effort for this program was performed under MSC/TRW Task 705-1 of Contract NAS 9-8166. The results of this effort and an interim version of the computer program are contained in the task report (Reference 17) and the program documentation (References 18 and 19) dated February 1972. The development effort was continued under MSC/TRW Task E-99 of Contract NAS 9-12330 and resulted in substantial modification to the interim version. This report describes the improved version of the program and supplants the portion of Reference 17 pertaining to the SSACPS program, and the entirety of Reference 18. The previous program listing (Reference 19) is replaced by the new program listing (Reference 20).

The objective of this program is to aid in the preliminary design and development of propulsion systems used for spacecraft attitude control. The program simulates the integrated operation of the many interdependent components typically comprising an attitude control propulsion system. Flexibility, generality, ease of operation, and speed consistent with adequate accuracy were overriding considerations during the development of this program.

Many excellent and detailed computer programs (such as the ICRPG rocket engine programs) were previously available for modeling specific components of fluid systems, and it was not the intent to duplicate this capability. However, such programs are often difficult to operate and are long-running. Furthermore, in general, they apply either to a single component or to a group of components in a fixed configuration. For these reasons, previously existing programs were not well suited for the simulation of large fluid systems in which many components operate interdependently, or for studies in which the system configuration is subject to alteration.

Simulation modules were developed representing the various types of fluid components typically encountered in an attitude control propulsion system (ACPS). These modules are basically self-contained and may be arranged by the program user into desired configuration through the program input data.

Optional capability has been built into many of the modules which permits the sizing of components to meet specified design criteria. For these reasons, this program can be used advantageously in the following areas of design and evaluation:

- . evaluation of candidate system configurations
- . preliminary design
- . performance prediction
- . sensitivity analysis
- . performance evaluation
- . malfunction simulation

Fluid property data and combustion characterizations for several propellants including cryogenics and earth storables have been included.

Note: In the following discussions, equations have been numbered, starting with (1), at the beginning of each section. Therefore, when referencing an equation, both the section and the equation number should be given.

## 2.0 PROGRAM PHILOSOPHY

An attitude control propulsion system is comprised of storage tanks, fluid transfer lines, junctions, regulators, valves, and thrust chambers. In addition, the system may contain gas generators, turbines, pumps, and heat exchangers. Typically, these components are connected in a manner such that the performance of any given component depends upon the performance of many, or all, of the other components. Evaluation of the performance of a given component in a coupled system generally requires consideration of its interdependence with adjacent components in the system. Typically, a simultaneous solution of the entire system is required.

A system is operating in steady-state when no conditions change with time. A system is said to be in quasi-steady-state if the system response rate is much faster than the rate of any time-varying forcing function. In the present program, only the storage tank module is time-dependent. The remainder of the components have sufficiently fast response rates so that instantaneous equilibrium can be assumed any given instant.

A quasi-steady state problem could entail the evaluation of a propellant tank and feed system operating in a blowdown mode. The performance history then is a succession of steady-state solutions corresponding to the slowly varying conditions in the tank at discrete time intervals.

To determine the steady-state operating point of a system, it is necessary to satisfy all the balances which exist in the system. These may include such considerations as mass conservation at a junction of several fluid lines, a power balance between a turbine and a pump, or a pressure continuity across an interface.

Anticipating the discussion of the method of solution (Section 3), the following simple system will serve to illustrate the basic approach employed in this program.

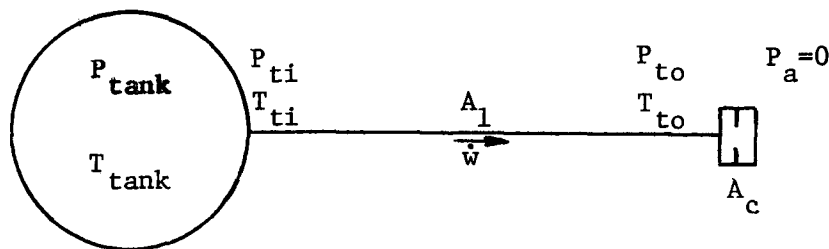


Figure 2.1 Sample Problem Schematic

A tank containing an ideal gas at pressure  $P_{\text{tank}}$  and ambient temperature  $T_{\text{tank}}$  discharges slowly into a vacuum through an orifice located at the end of a short line. If the flow area of the line ( $A_1$ ) is large in relation to the area of the orifice ( $A_c$ ), the gas velocity is low, and the line may be regarded as frictionless. Under these conditions the gas temperature in the line is near ambient so that the line may be assumed to be adiabatic.

In physical systems of this type, steady-state flow conditions arise naturally in a way that it is possible to identify relationships between the various flow parameters such as flowrates, pressures, and temperatures. A proper model of a physical system must satisfy those relationships which exist in the physical system.

In the example system, the relationships can be identified at once. Most of the relationships are used to compute the values of unknown quantities from input or previously computed quantities. Starting with the given quantities, calculation proceeds in the downstream direction in the following manner. The total conditions at the line inlet are obtained directly from the tank conditions.

$$P_{t_1} = P_{\text{tank}} \quad (\text{Total Pressure}) \quad (1)$$

$$T_{t_1} = T_{\text{tank}} \quad (\text{Total Temperature}) \quad (2)$$

There is no basis yet for defining the flowrate,  $\dot{w}$ . Variables which cannot be calculated directly in terms of other known quantities are designated as state variables. Initial estimates of the values of state variables must be provided by the user. Subsequently, these values will be systematically adjusted to satisfy various constraining relationships which will be required at positions located downstream in the flow path.

Having provided such an estimate of  $\dot{w}$ , it then becomes possible to proceed with the calculations next in order. The line inlet static pressure and temperature and the fluid properties may be obtained by iteration from the following relationships contained in a line module.

$$V = 144 \dot{w} / \rho A_1 \quad \text{Velocity} \quad (3)$$

$$T_{t_1} = T_{t_1} - V^2 / 2g_c C_p \quad \text{Static temperature} \quad (4)$$



$$P_i = P_{ti} \left( \frac{T_i}{T_{ti}} \right)^{\frac{\gamma}{\gamma-1}} \quad \text{Static pressure} \quad (5)$$

$$\rho = \phi_1(P_i, T_i) \quad \text{Density} \quad (6)$$

$$C_p = \phi_2(P_i, T_i) \quad \text{Specified heat} \quad (7)$$

$$\gamma = \phi_3(P_i, T_i) \quad \text{Specified heat ratio} \quad (8)$$

Since the line is assumed frictionless and adiabatic, no processes are present which alter the properties of the gas, and the outlet conditions are obtained directly from the inlet conditions

$$P_{to} = P_{ti} \quad (9)$$

$$T_{to} = T_{ti} \quad (10)$$

$$P_o = P_i \quad (11)$$

$$T_o = T_i \quad (12)$$

In the case of a more general problem requiring consideration of friction and possibly heat transfer, more detailed line modules are available which employ additional relationships. In any event, the line outlet conditions are completely specified by the inlet conditions and perhaps other pre-scribed input data.

Having completed the necessary line calculations, execution passes to the next designated module, in this case the orifice module. The gas properties computed at the line outlet are used directly in the orifice module. Since the flow exhausts to a vacuum, a choking pressure ratio exists:  $P_a/P_{to} \leq \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma}{\gamma-1}}$ , and sonic conditions prevail at the orifice throat. At this point a unique relationship exists and must be satisfied between the flowrate, the choking area, and the gas properties, represented by the following equation

$$\dot{w}_c = P_{to} A_c \sqrt{\frac{g_c \gamma}{RT_{to}}} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}, \quad (13)$$

where the gas constant  $R$  is evaluated from known properties as  $R = C_p(\gamma-1)/\gamma$ .

In general, the estimated value of  $\dot{w}$  used earlier will not agree with this choking flowrate. That these values must be equal forms the basis of a constraining relationship. The relative disparity of these values may be indicated by the function

$$f = 1 - \dot{w}/\dot{w}_c . \quad (14)$$

The value of the state variable  $\dot{w}$  must be found which drives  $f$  to zero.

In this simple case, the value is obvious. However, the problem becomes nontrivial when the line is replaced with a smaller line in which friction plays a significant role. Both  $P_{to}$  and  $T_{to}$  vary with  $\dot{w}$ , and  $\dot{w}_c$  therefore is no longer constant. Furthermore, typical problems generally contain many state variables which have a combined influence on each of several constraint equations making the balancing problem far out of reach of manual methods. With the aid of the computer, a precisely balanced operating point of a system requiring 20 state variables can be obtained in the order of one minute.

At this point, the physical mechanisms relating  $\dot{w}$  and  $f$  have been established. A second pass through the component modules, this time using a perturbed value of the state variable  $\dot{w} + \Delta\dot{w}$ , produces a different error  $f + \Delta f$ . The sensitivity of  $f$  to variations in  $\dot{w}$  is

$$\frac{(f + \Delta f) - f}{(\dot{w} + \Delta\dot{w}) - \dot{w}} = \frac{\Delta f}{\Delta\dot{w}} \approx \frac{df}{d\dot{w}} \quad (15)$$

which is an approximation to the analytic derivative of  $f$  with respect to  $\dot{w}$ . Employing the finite-different adaptation of the Newton-Raphson method (Secant Method), a better estimate of  $\dot{w}$  is given by

$$\dot{w}^{n+1} = \dot{w}^n - f^n / \left( \frac{\Delta f}{\Delta\dot{w}} \right) \quad (16)$$

$$f^{n+1} = f(\dot{w}^{n+1}) \quad (17)$$

Equations (16) and (17) are evaluated repeatedly, producing successively better estimates of  $\dot{w}$  until a specified level of agreement is achieved. This method is readily extended to functions of several variables, and if the

functions are well behaved, convergence can occur quite rapidly. In the original sample problem, convergence would occur in a single iteration. With line friction included, about six iterations would be needed. Realistic checkout cases involving 14 state variables achieved precise convergence in 9 iterations, requiring just 3 seconds of computer time. The philosophy employed in the program may be summarized as follows:

1. A physical system is modeled as a collection of interdependent components.
2. Modules are provided to simulate the function of each system component.
3. The component modules are executed in sequence following the physical flowpath.
4. Data are carried from one module to the next. Each component depends only upon the performance of its upstream components, fixed boundary conditions, and current values of specific state variables.
5. The values of flow parameters in a module which cannot be defined directly in terms of data input to that module (from upstream component modules or boundary conditions) are designated as state variables. The user provides initial estimates of the values. These values subsequently are adjusted to make the system variables self-consistent. The associated constraint functions arise in downstream component modules.
6. Constraint functions are generated (either automatically or by specified design constraints) whenever a physical relationship must be imposed between the system variables. Constraint functions indicate relative degrees of internal inconsistency arising with a particular choice of state variable values.
7. A non-linear equation solver monitors the values of the constraint functions and systematically adjusts the values of the state variables in such a way as to minimize the inconsistency. If the problem is well-posed, a simultaneous system solution is obtained when the constraint values go to zero.

### 3.0 METHOD OF SOLUTION

#### 3.1 System Definition

A physical system is comprised of a group of fluid components arranged in a specific configuration which operate interdependently subject to various boundary conditions. In this program, component modules are available to simulate the essential function of those fluid components typically used in spacecraft altitude control propulsion systems. In general, for each function served by a component in the physical system, there exists one or more corresponding simulation modules.

In some cases more than one component module must be used to represent a physical component. For example, a turbopump is represented by a turbine module and a separate pump module which operate dependently, being linked by shaft speed and power balance. A gas line with sonic conditions existing at the outlet (e.g. choked turbine exit duct) is represented by a line module followed by an exit module, the latter imposing the necessary choking flow constraint.

The system is divided into its component parts in a manner consistent with the available simulation modules. The execution sequence for these modules is specified by the user. For most economical use of state variables, the sequence should start at the beginning of a flowpath and proceed in the downstream direction. In this way, information necessary at a component inlet will be available from prior calculation at the adjacent upstream component. Where several flow paths merge, the sequences for each flow path are simply strung together. The order in which the flow paths are considered is not important; however, all the component modules in each upstream flow path should be executed before executing a module in which the flow paths merge (i.e. a junction or a bipropellant combustion chamber). Systems employing a closed loop in which a flow path is diverted from the mainstream and returned to an upstream point, as in a bootstrap turbopump configuration, are admitted by the program through the use of the feedback capability described in Section 3.4.

Simulation modules for nine types of components have been developed, several of which have a number of varieties or optional capabilities. For example, four varieties of fluid transfer lines are available, and the combustion chamber module serves both as a thrust chamber and gas generator.

Each component module simulates a component type and is used repeatedly to represent each of the system components of a common type. The components are assigned identification numbers between one and N, where N is the maximum number of components of each type as given in Section 4.0. Each component, then, is specified by its type and its identification number. Assigning the identification number 1 to the components in the example system, the execution sequence becomes SYSCOM = TANK (1), LINE (1), CHOKE (1). Assigning different identification numbers, an equivalent system could have been SYSCOM = TANK (3), LINE (8), and CHOKE (2).

All system components are considered to be connected by fluid transfer lines. The line module provides the basic means by which data is transferred from one component module to the next. Component connections are made in a patchboard manner. By user input, specific line numbers are associated with the inlets and the outlets of each of the other components. In the example, the TANK (1) outlet is connected to the inlet of LINE (1). Upon completion of the tank calculations, the necessary data is loaded directly into the LINE (1) input storage locations. Upon completion of the LINE (1) calculations, the data is stored in the LINE (1) output locations. Having specified the number of the line connected to the exit module, input data to CHOKE (1) is obtained directly from the output locations of LINE (1). The actual data specifications would be LDMO = 1, LCHOKE = 1.

The system components are defined simply by loading the necessary characterization data for each. Depending upon the specific configuration and options employed, the amount of required input data for each module will vary. Data requirements and module options are discussed thoroughly in Section 4.0 (Component Module Descriptions). An input processor named TRWLOD is used which makes data loading quite easy.

### 3.2 State Variables

Certain program variables may be designated by the user as state variables. State variables are introduced where ever insufficient information exists by which the value of a program variable can be defined. In the example problem the flow rate  $\dot{w}$  was the only state variable. In typical problems, 10 to 20 state variables are common, and as many as 40 are permitted by the program. The ordered set of state variables is termed the state vector. State variables are the basic program unknowns, the values of which are determined in such a way as to be self-consistent with the other program variables. The following list shows the 22 program variables which can be designated as state variables along with component modules in which they are introduced. (The actual computer names may be found in Appendix B).

<u>Variable</u>	<u>Description</u>	<u>Units</u>	<u>Module</u>
L	Line length	(ft)	Line
D	Line diameter	(in)	Line
$\dot{w}$	Line flow rate	(lbm/sec)	Line
$P_i$	Line inlet static pressure	(psi)	Line
$T_i$	Line inlet static temperature	(°R)	Line
$C_d A$	Effective flow area	(in <sup>2</sup> )	Valve
$A_{ch}$	Choking flow area	(in <sup>2</sup> )	Choked exit
$A_{inj1}$	Flow area, injector 1	(in <sup>2</sup> )	Chamber
$A_{inj2}$	Flow area, injector 2	(in <sup>2</sup> )	Chamber
$A_t$	Nozzle throat area	(in <sup>2</sup> )	Chamber
$\epsilon$	Nozzle expansion ratio	(-)	Chamber
$D_T$	Turbine rotor diameter	(in)	Turbine
$A_T$	Effective turbine inlet flow area	(in <sup>2</sup> )	Turbine
$N_T$	Turbine speed	(RPM)	Turbine
$P_{To}$	Turbine outlet pressure	(psi)	Turbine
$R_{PD}$	Pump diameter ratio	(-)	Pump

$P_T$	Turbine power to pump	(ft-lbf/sec)	Pump
$R_G$	Pump/turbine gear ratio	(-)	Pump
$L_{HX}$	Heat exchanger length	(in)	Heat exchanger
$R_{HXi}$	Radius, heat exchanger inside tube	(in)	Heat exchanger
$R_{HXo}$	Radius, heat exchanger outside tube	(in)	Heat exchanger
$P_{\text{tank}}$	Tank pressure	(psi)	Tank
$P_{\text{reg}}$	Regulator pressure	(psi)	Regulator

Program variables are designated as state variables simply by placing the names of the desired state variables in a list. An identification number of the particular components associated with the state variables follows each name. The input data statement  $\text{STATE} = \text{WDOT},1, \text{ARINJ2},4, \text{PTANK},3$  specifies the following as state variables: flowrate ( $\dot{w}$ ) in line 1, injector two area ( $A_{\text{inj2}}$ ) of combustion chamber 4, and the tank pressure ( $P_{\text{tank}}$ ) of storage tank 3. Here, the state vector contains three elements which are the estimates of the flow rate, injector area, and pressure.

### 3.3 Constraint Equations

A system steady-state operating point is determined only when all the physical relationships applicable to the system are satisfied. The relationships include component performance characterization curves and thermodynamic property tables as well as the various conservation equations and other mechanical and thermodynamic relationships. Many of these relationships are used for computational purposes to advance from one point in the flowpath to the next. The values of newly encountered variables are defined simply in terms of previously computed, or externally specified, values.

However, at some point, a necessary physical relationship will occur in which all the quantities have been specified. If this relationship is not satisfied identically, it becomes the basis of a constraint on the values of the state variables. In the example problem, the relationship applicable at a sonic orifice is

$$\dot{W} = P_t A \sqrt{\frac{g_c \gamma}{RT_t} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad (1)$$

Since all the variables in this equation are specified by input, or by prior calculation, it cannot be generally satisfied. Defining a new variable  $\dot{W}_c$  (choking flowrate) computed from Equation (1), the discrepancy between the required flowrate ( $\dot{W}$ ) and the interim flowrate ( $\dot{W}$ ) resulting from state variables estimated is  $\dot{W}_c - \dot{W}$ . In the interest of numerical stability, this discrepancy is normalized with respect to a convenient, non-zero quantity which in this case is chosen to be  $\dot{W}_c$ . The relative degree to which Equation (1) is not satisfied may be indicated by the function

$$f = 1 - \dot{W}/\dot{W}_c \quad (2)$$

Extending this example to the general case, some system variable,  $u$ , is related to some other system variables  $y_1, y_2, \dots$  by an equation of the form

$$u = G(y_1, y_2, \dots) \quad (3)$$

This equation must be satisfied by a proper choice of the state variable values, and is called a constraint equation.



At a given iteration  $k$ , a reference quantity, is defined as

$$u_{\text{ref}}^k = G(y_1^k, y_2^k, \dots), \quad (4)$$

and the current relative discrepancy between  $u^k$  and  $u_{\text{ref}}^k$  is given by

$$f^k = 1 - u^k / u_{\text{ref}}^k. \quad (5)$$

Care has been exercised in formulating the constraint equations so that the resulting constraint functions (Equation 5) are smooth and vary monotonically with changes in the program variables  $u, y_1, y_2, \dots$ . The constraint Equation(3) is satisfied when  $f=0$ .

Constraint equations arise in two ways, the first one described above being necessary for internal consistency among the system variables. Since the requirement for constraints of this type exists whenever the associated component modules are executed, the program has been designed to impose these constraints automatically. The following is a list of such constraints.

<u>Constrained Variable</u>	<u>Reference Variable</u>	<u>Description</u>	<u>Module</u>
$P_{\text{cw}2}$	$P_{\text{cw}1}$	Equal flow pressures (Bi)	Chamber
$P_c$	$P_{\text{cw}}$	Flow vs combustion $P_c$ (thrustor)	Chamber
$\dot{W}$	$\dot{W}_c$	Choked flow boundary	Choke
$P_{\text{ti}}$	$P_{\text{tJ}}$	Junction to line pressure	Feedback
$T_{\text{ti}}$	$T_{\text{tJ}}$	Junction to line temperature	Feedback
$P_o$	$P_J$	N-1 junction inlet pressures	Junction
$\Sigma W_i$	$\Sigma W_o$	Net flow $(W_i - W_o) / (W_i - W_o)_{\text{initial}}$	Junction
$P_T$	$P_P$	Turbine to pump power	Pump
$P_o$	$P_{\text{tank}}$	Line to tank inlet pressures	Tank
$\dot{W}$	$\dot{W}_{\text{cT}}$	Inlet nozzle choking flowrate	Turbine

The second type of constraints arises from optionally specified system design conditions which may be imposed in addition to the automatic constraints.

The user generates these constraints by specifying desired values of certain program variables. For example, by specifying a desired chamber pressure ( $P_{cD}$ ) along with an associated state variables such as the combustor throat area,  $A_t$ , a solution will be obtained which satisfies the physical requirements of the system and also produces the desired chamber pressure ( $P_c = P_{cD}$ ). For this type,  $G$  in Equation (4) is a constant equal to the design value input by the user.

Below is the list of additional constraints which may be imposed for design purposes.

<u>Variable</u>	<u>Description</u>	<u>Units</u>	<u>Usage</u>
$P_{oD}$	Outlet static pressure	psi	Line
$P_{cD}$	Chamber pressure	psi	Chamber
$MR_D$	Mixture ratio	-	Chamber
$F_D$	Thrust	lbf	Chamber
$I_{spD}$	Specific impulse	lbf-sec/lbm	Chamber
$T_{HXa}$	Outlet temperature, side a	°R	Heat exchanger
$T_{HXb}$	Outlet temperature, side b	°R	Heat exchanger
$\Delta P_P$	Pressure drop across pump	psi	Pump
$\Delta P_L$	Pressure drop across line	psi	Line
$\Delta P_V$	Pressure drop across valve	psi	Valve

The constraint equations relate the constraint values (f) to the state variables or to system variables which in turn are related to the state variables. For the typical systems considered to date, the number of constraints employed has varied between 5 and 25, with as many as 40 being permitted. The resulting system of  $n$  equations in  $n$  unknowns is evaluated by the program equation solver. For a properly posed problem, the set of constraint values can be driven to zero simultaneously only with a unique set of values of the state variables (solution vector). Any deviation of the state vector from the solution vector results in one or more of the constraint equations not being satisfied.

### 3.4 Feedback Loops

Propulsion systems frequently have closed flow paths in which a portion of the flow is tapped off of the main flow and diverted back to a point upstream to perform a function which influences the main stream flow. Examples include the bootstrap turbopump feed system illustrated below, and tank pressurization systems.

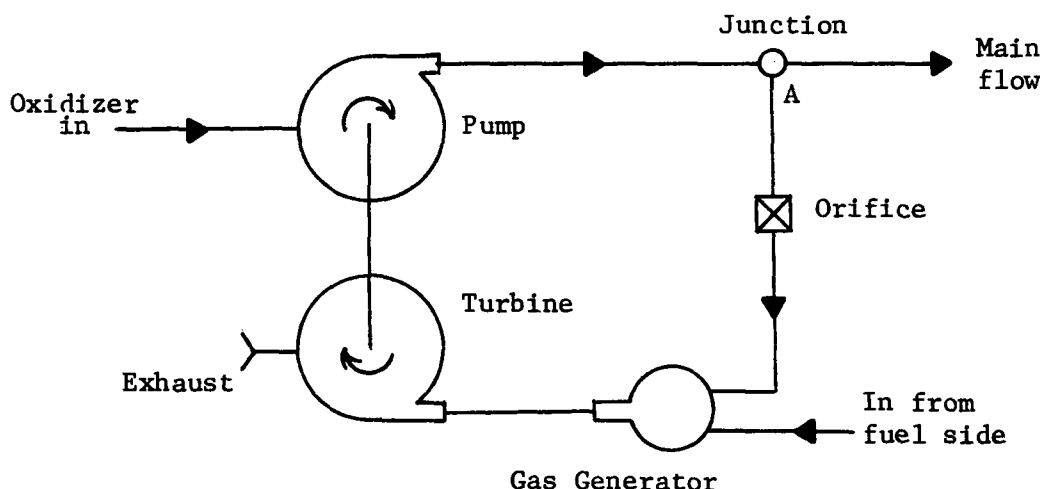


Figure 3.1 Bootstrap Feed System Illustration Feedback Loop

The formulation of this program requires a starting point in the flow path on which the performance of downstream components can be based. For a system with a closed loop flow path, the starting point is obtained by the following procedure. The loop is broken (conceptually) at the beginning of the feedback line which is the point at which the return flow diverts from the main stream. In Figure 3.1, this point is indicated as point A. The feedback line thus becomes the first component in the feedback flow path. As formulated, the breakpoint always occurs adjacent to a junction, and the necessary logic is incorporated in the junctions module.

Since the feedback line is connected to a junction outlet, per Section 4.2, the line flow rate variable  $\dot{W}_1$  must be designated as a state variable and provided an initial estimate. There is no basis for defining the values of the pressure and temperature variables in the feedback line, so that they, too, must be designated as state variables and assigned initial estimates.

Upon executing the components in the feedback loop, the junction conditions become known. Equality of the total pressure and total temperature across the junction-line interface is obtained by automatically imposing the constraints

$$f = 1 - P_{ti}/P_{tJ} \text{ and} \quad (1)$$

$$f = 1 - T_{ti}/T_{tJ}. \quad (2)$$

### 3.5 Equation Solver

During the execution of the system component modules, the constraint equations generate values for the elements of the constraint vector  $\underline{f} = (f_1, f_2, \dots, f_n)$ . This vector indicates the relative error in achieving internally consistent operating conditions plus any user-imposed design requirements. It is the function of the program equation solver to monitor the constraint vector and to adjust the state vector  $\underline{X} = (X_1, X_2, \dots, X_n)$  as necessary to drive the constraint vector to zero. As presently formulated, the program may consider as many as forty independent constraint equations which depend upon a like number of independent state variables.

Since the equation solver is of central importance in the formulation of this program, a brief derivation of the method employed will be given. Consider a set of  $n$  functions  $A_i, i=1, 2, \dots, n$  which depend on  $n$  independent variables  $X_j, j=1, 2, \dots, n$  such that

$$f_i = A_i(X_1, X_2, \dots, X_n), \quad i=1, 2, \dots, n. \quad (1)$$

Given a specific state vector  $\underline{X}^0$ , the constraint value corresponding to the  $i^{\text{th}}$  constraint equation is

$$f_i^0 = A_i(\underline{X}^0). \quad (2)$$

The function  $A_i$  can be expanded in a Taylor series about the point  $(f^0, \underline{X}^0)$  producing

$$f_i^1 = f_i^0 + \left. \frac{\partial A_i}{\partial X_j} \right|_{\underline{X}^0} (X_j^1 - X_j^0) + 0(X^1 - X^0)^2, \quad (3)$$

where  $0(X^1 - X^0)^2$  indicates additional terms of second order and higher in the small quantities  $(X^1 - X^0)$ . The repeated index  $j$  indicates summation over the values  $j=1, 2, \dots, n$ .

The value  $f_i^1 = A_i(\underline{X}^1)$  may be estimated to first order accuracy in terms of quantities known at  $\underline{X}^0$  by the equation

$$f_i^1 = f_i^0 + \left. \frac{\partial A_i}{\partial x_j} \right|_{\underline{X}^0} (\underline{X}_j^1 - \underline{X}_j^0). \quad (4)$$

This equation represents a tangent plane to the surface  $f_i - A_i(\underline{X}) = 0$  in the neighborhood  $\underline{X}^1 \approx \underline{X}^0$ .

Equation (4) can be written in matrix form as

$$[f^1] = [f^0] + [P] [\Delta X], \quad (5)$$

where  $[P]$  is an  $n \times n$  matrix of the partial derivatives of  $A$ , the elements of which are defined by

$$P_{ij} = \partial A_i / \partial X_j, \quad (6)$$

and  $[\Delta X]$  is the column vector with the components

$$\Delta X_j = X_j^1 - X_j^0. \quad (7)$$

The constraint vector  $\underline{f}^0$  results from a state vector  $\underline{X}^0$ . The problem is to find the solution vector which produces  $\underline{f} \approx \underline{0}$ . Putting  $\underline{f}^1 = \underline{0}$ , an estimate of the solution vector  $\underline{X}^1 = \underline{X}^0 + \underline{\Delta X}$  may be obtained by solving Equation (5)

for  $\underline{\Delta X}$ :

$$[P] [\Delta X] = - [f^0]. \quad (8)$$

Premultiplying by the matrix inverse  $[P]^{-1}$ ,

$$[P]^{-1} [P] [\Delta X] = - [P]^{-1} [f^0], \quad (9)$$

or

$$[\Delta X] = - [P]^{-1} [f^0]. \quad (10)$$

The improved estimate of the solution state vector becomes

$$[X^1] = [X^0] - [P]^{-1} [f^0], \quad (11)$$

and the corresponding constraint vector is

$$\underline{f}^1 = A(\underline{X}^1). \quad (12)$$

If A is a linear system of equations so that  $\underline{f}^1$  is given exactly by Equation (4), then  $\underline{X}^1$  given by Equation (11) is the solution vector. In general, however, Equation (4) is approximate and  $\underline{X}^1$  resulting from Equation (11) is only an improved estimate. Further improvement is achieved by replacing  $\underline{X}^0$  with  $\underline{X}^1$  and  $\underline{f}^0$  with  $\underline{f}^1$  and repeatedly applying Equations (11) and (12). This process is continued until the resulting constraint vector is acceptably close to zero.

The size of the constraint vector is suitably indicated by its Euclidean norm defined by

$$||f|| = \frac{1}{n} \left[ \sum_{i=1}^n f_i^2 \right]^{\frac{1}{2}} \quad (13)$$

Convergence of the iterative process may be inferred when the norm after some  $k^{\text{th}}$  iteration satisfies the criterion

$$||f||^k \leq \epsilon, \quad (14)$$

where  $\epsilon$  is a preset constant typically on the order of  $10^{-6}$ .

If the  $[P]^{-1}$  matrix is evaluated at the points  $(\underline{X}^0)$  for each iteration  $k$ , the method described above is the multi-dimensional version of the Newton-Raphson method. An example of the convergence process obtained with this method is shown below for a function of a single variable ( $n=1$ ).

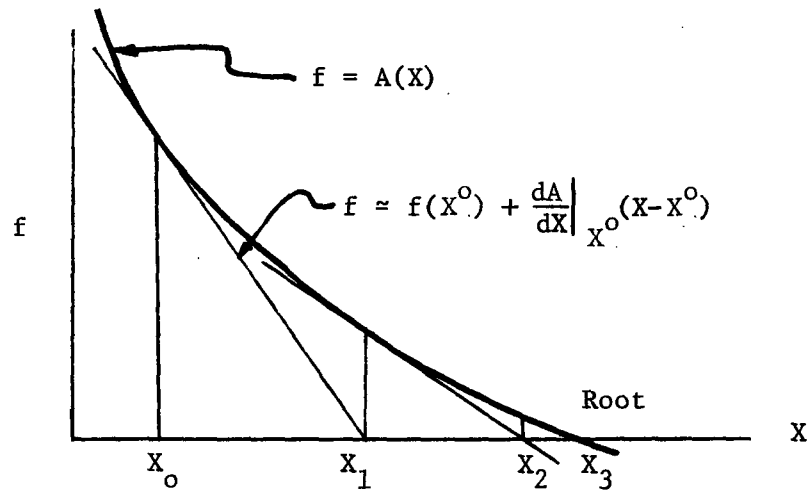


Figure 3.2 Example of Newton-Raphson Method

The continuous function  $A$  illustrated here varies monotonically with  $X$ , has a continuous first derivative and a second derivative which does not change sign, and intersects the  $X$ -axis at a computationally distinct point. These are characteristics of a well-behaved function. Under these conditions, the Newton-Raphson method possesses the property of quadratic convergence which implies a doubling of the number of significant digits in the state variable with each additional iteration as the solution is approached (Reference 1).

For problems in which calculation of the partial derivatives and the matrix inverse is arduous, overall computer time sometimes can be decreased by the following modification. At the expense of a slower convergence rate, the partial derivatives and the inverse matrix are computed one time only at the initial estimate  $\underline{X}^0$  and applied without change at succeeding  $\underline{X}^k$ . This constant slope method applied to the function in Figure 3.2 produces the following iteration process.

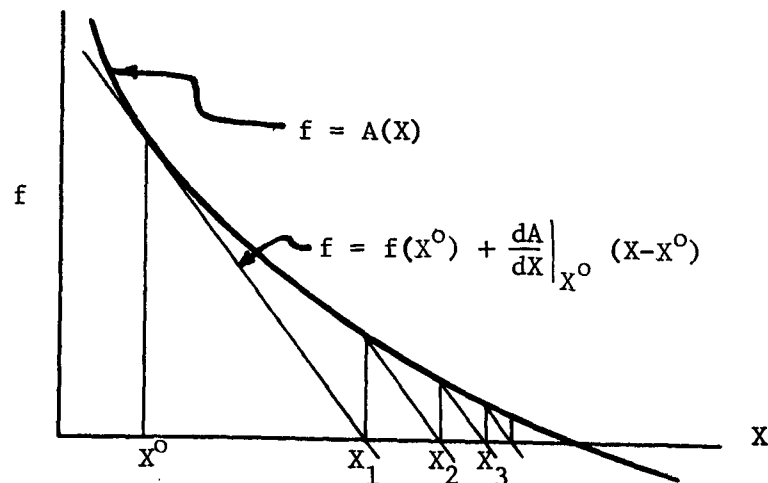


Figure 3.3 Example of Constant Slope Method



The complexity of the component modules and the flexibility of design-ating the execution sequence, state variables, and optional design constraints generally preclude any attempt to formulate analytically the functions  $A_i$  or the partial dervatives  $\partial A_i / \partial X_j$ . This problem can be circumvented by approximating the derivatives with their finite-difference representations. Referring to Equation (4),  $\partial A_i / \partial X_j$  is approximated to first order accuracy by the relation

$$\frac{\partial A_i}{\partial X_j} \approx \frac{f(X_j^1) - f(X_j^0)}{X_j^1 - X_j^0} = \frac{f(X_j^0 + \Delta X) - f(X_j^0)}{\Delta X} \quad (15)$$

The method then becomes the secant method and the iteration process can be illustrated as follows.

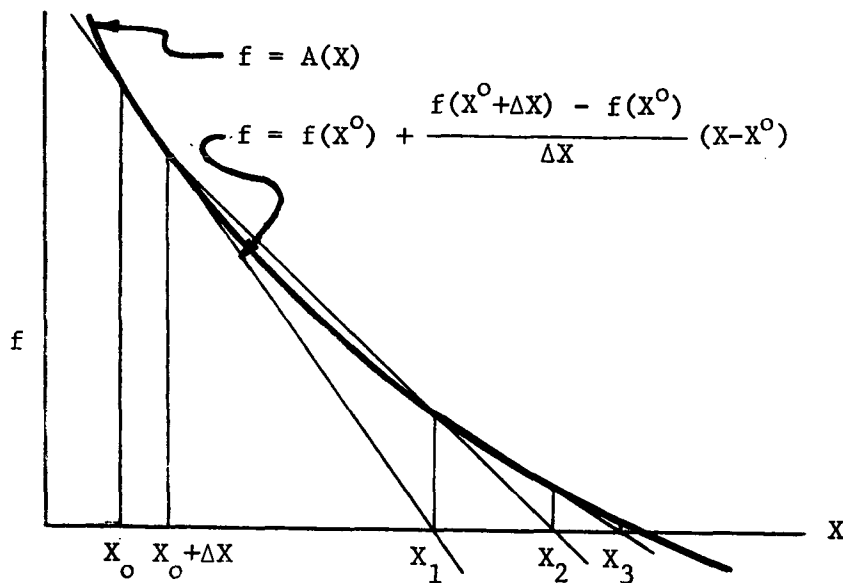


Figure 3.4 Example of Secant Method

Having presented a discussion of the general methods, the specific procedures needed to implement the combination of these methods used in the program will now be given. It was mentioned in Section 3.3 that the constraint functions are normalized with respect to characteristic reference quantities. This scaling procedure places approximately equal emphasis on each of the constraints, and has the effect of reducing truncation error and increasing the computational stability. For similar reasons, the state variables are normalized with respect to reference quantities  $X_j \text{ ref}$  supplied by the user. The normalized state variables are defined by

$$y_j = X_j / X_j \text{ ref} \quad (16)$$

The constraint vector  $\underline{f}(\underline{X})$  is evaluated in a subroutine containing the appropriate component module execution sequence. The state variables  $X_j$  required are obtained as

$$X_j = y_j \cdot X_j \text{ ref} \quad (17)$$

The initial values of the partial derivatives  $\partial A_i / \partial y_j$  forming the matrix  $[P]$  are obtained by sequentially perturbing the individual elements by two percent of the reference state vector producing

$$\frac{\partial A_i}{\partial y_j} = \frac{f_i(y_j + \Delta y_j) - f_i(y_j^0)}{\Delta y_j}, \quad (18)$$

where  $\Delta y_j = 0.02$  for all  $j$ .

Several methods for obtaining matrix inverses were evaluated. A self-contained subroutine GJR available on the Univac 1108 Math-Pac library was selected. This routine employs Gauss-Jordan elimination with pivoting and has proven to be fast and reliable.

During the generation of the partial derivative matrix, if the norm of constraint vector corresponding to the perturbed state vector is less than the previous norm, the initial-guess state vector is updated.

The following operations are performed at each iteration level. A correction vector ( $\Delta y$ ) is computed according to the equation

$$\Delta y_j = \sum_{i=1}^n P_{ji}^{-1} f_i . \quad (19)$$

Convergence is assumed when no significant adjustments to  $y$  are indicated. The criteria is

$$|\Delta y_j| \leq \epsilon_{\Delta y}, \quad (20)$$

where  $\epsilon_{\Delta y}$  is a constant typically on the order of  $10^{-6}$ .

The step size permitted by each state variable is limited to a prescribed fraction of the reference quantity

$$|\Delta y_j| \leq \Delta y_{\max}.$$

where  $\Delta y_{\max}$  is a constant input by the user.  $\Delta y_{\max} = 0.3$  is typical. To dampen any oscillatory motion of the state vector about the solution, the following additional limitation is placed on the permissible values of  $\Delta y_j$ . For each value of  $j$ , whenever the sign of  $\Delta y_j$  changes from one iteration to the next, the magnitude of the new correction is limited to one half of the corresponding magnitude from the previous iteration. Symbolically,

$$\text{if } \frac{\Delta y_j^k}{\Delta y_j^{k-1}} < -\frac{1}{2}, \text{ then } \Delta y_j^k = -\frac{1}{2} \Delta y_j^{k-1} . \quad (21)$$

This limit is quite useful for certain poorly behaving functions.

A new estimate of the normalized state vector is obtained by

$$y_j^1 = y_j^0 - \Delta y_j . \quad (22)$$

Upper and lower bounds on  $y_j$  may be imposed by the user according to

$$y_{j \min} \leq y_j^1 \leq y_{j \max}. \quad (23)$$

Using the updated vector  $\underline{y}^1$  the corresponding constraint vector is then computed. If the constraints are not better satisfied ( $\|\underline{f}^1\| < \|\underline{f}^0\|$ ) the length of the correction vector  $\underline{\Delta y}$  is shortened by half and reapplied to the previous state vector. This process can repeat as many as three times resulting in a correction vector 1/8 as long as original. This process is useful in achieving convergence of strongly nonlinear constraint functions.

Having developed a new estimate of the state vector, a call to the subroutine executing the component modules produces a new corresponding constraint vector  $\underline{f}^1$ . Convergence is assumed if  $\underline{f}^1$  is sufficiently small. The convergence criteria is

$$\|\underline{f}^1\| \leq \epsilon_f, \quad (24)$$

where  $\epsilon_f$  is an input constant on the order of  $10^{-6}$ . If convergence is not achieved, the current vectors  $\underline{y}^1$  and  $\underline{f}^1$  replace the stored values from the previous iteration

$$y_j^0 = y_j^1 \text{ and } f_i^0 = f_i^1, \quad (25)$$

and the operations indicated by equations (19) through (24) are repeated.

The method described above is basically the constant slope method using partial derivatives obtained from finite difference approximations. If the constraint functions are reasonably linear, little is gained by recomputing them at each iteration. However, if the constraint functions are sufficiently non-linear and the initial estimate of state vector is poor, the linearized functions, Equation (4), based upon this estimate may poorly represent the true functions  $A_i$  in the vicinity of the current estimate. The computed correction vectors ( $\underline{\Delta y}$ ) thus can be considerably

in error resulting in slow convergence, or divergence.

To combat this condition, the ability has been built into the equation solver to selectively update the partial derivative matrix based upon the excursion of individual elements of the state vector. The values of  $y_j$  at which the partial derivatives  $\partial A_i / \partial y_j$  are evaluated are stored in  $\tilde{y}_j$ . The  $j^{\text{th}}$  column of [P] is updated at the current  $y$  whenever the excursion in  $y_j$  exceeds a preset constant

$$|y_j - \tilde{y}_j| > \Delta \tilde{y}_j, \quad (26)$$

where the  $\Delta \tilde{y}_j$  typically are around 0.3. By setting the  $\Delta \tilde{y}_j$  large, the constant slope method is employed. By setting  $\Delta \tilde{y}_j = 0$ , the partial derivatives are recomputed for each state variable at each iteration, and the resulting procedure is the finite-difference adaptation of the Newton-Raphson method.

#### 4.0 COMPONENT MODULE DESCRIPTIONS

Component modules are provided which simulate the essential function of components typically used in spacecraft attitude control propulsion systems. These component modules are self-contained and generally serve a single function. Within certain restrictions they may be interconnected in a manner completely at the discretion of the user. The quantities output from a component module are determined entirely from component specifications, flow conditions at the component inlet, and values of state variables associated directly with the component module. The sequence in which the modules are executed is defined by the user.

In keeping with the stated scope of this program, the modules are sufficiently detailed to model the basic functional relationships applicable to the components. The quantitative accuracy is appropriate for preliminary design purposes. Simplifying assumptions have been introduced where warranted to maintain program generality, computational speed, and ease of operation. Considerable use has been made of the perfect gas and isentropic flow assumptions. These and other idealizations are discussed in more detail under the specific module descriptions.

Below is a list of the ten component modules currently available. Each of these modules may be used a number of times to represent different components of the same type. The maximum number of components of each type is limited only by the storage space allocated and is shown in the adjacent column.

	<u>Component Type</u>	<u>Maximum Number</u>
. Line		70
	Frictionless adiabatic	
	Adiabatic (gas)	
	Isothermal (gas)	
	Friction and heat transfer (liquid or gas)	
. Junction		10
. Choked Exit		10
. Storage Tank/Accumulator		10
. Valve/Orifice/Check Valve		30
. Pressure Regulator		10

<u>Component Type</u>	<u>Maximum Number</u>
. Thrust Chamber/Gas Generator	10
. Gas Turbine	5
. Centrifugal Pump	5
. Heat Exchanger	5

#### 4.1 Lines

Fluid transfer lines are considered the basic components by which all other physical components are interconnected. The five line modules described below serve two functions: 1) they model the effects of friction and heat transfer occurring in fluids flowing in constant area ducts; and 2) they provide a convenient means of transferring data from the outlet of one component module to the inlet of the next. The number of a line connected to a component outlet is available in the component module, and upon completion of the component module calculations, the outlet quantities are loaded directly into the downstream line module.

The standard inlet conditions of a line module consist of the flow rate  $\dot{w}$ , the static pressure  $P_i$ , and the static temperature  $T_i$ , where the pressure and temperature may be designated as state variables. However, the appropriate outlet quantities from some components are the total pressure  $P_t$  and the total temperature  $T_t$ . In this case, the following preliminary calculations are performed iteratively to obtain the line static inlet conditions.

$$P_i \approx P_{ti} \quad (1)$$

$$T_i \approx T_{ti} \quad (2)$$

$$\left. \begin{array}{l} \rho = \phi_1(P_i, T_i) \\ C_p = \phi_2(P_i, T_i) \\ \gamma = \phi_3(P_i, T_i) \end{array} \right\} \text{Property data} \quad (3)$$

$$C_p = \phi_2(P_i, T_i) \quad (4)$$

$$\gamma = \phi_3(P_i, T_i) \quad (5)$$

$$V = 144 \dot{W} / \rho A \quad (6)$$

$$T_i = T_{ti} - V^2 / 2g_c C_p \text{ (gas)} \quad (7a)$$

$$T_i = T_{ti} \quad \text{(liquid)} \quad (7b)$$

$$P_i = P_{ti} \left( \frac{T_i}{T_{ti}} \right)^{\frac{\gamma}{\gamma-1}} \text{ (gas)} \quad (8a)$$

$$P_i = P_{ti} - V^2 / 2g_c \text{ (liquid)} \quad (8b)$$



The symbols  $\phi_1$ ,  $\phi_2$ , and  $\phi_3$  represent thermodynamic property functions. Note that different equations are used for liquids and for gases. After iterating twice as shown by the loop, additional property data is obtained for use in the designated line module.

Five different line modules were created to provide the user an easy means of specifying boundary conditions appropriate for specific fluid transfer lines.

Frictionless/Adiabatic Line - The first type of line assumes frictionless and adiabatic flow conditions, and can be used for either liquids or gases. This line introduces no effects on the flow. Its main use is in transferring data between component modules. A physical line may adequately be modeled as a frictionless-adiabatic line if the flowrate is small relative to the flow area, and the fluid is either thermally insulated from the surroundings or near ambient temperature. The outlet conditions are:

$$P_{to} = P_{ti} , \quad (9)$$

$$T_{to} = T_{ti} , \quad (10)$$

$$P_o = P_i , \quad (11)$$

$$\text{and } T_o = T_i . \quad (12)$$

Adiabatic Line - The adiabatic line module is the second line type. This module includes friction but assumes zero heat flux into a perfect gas. The friction factor is obtained from a correlation in terms of the Reynolds number for fully developed turbulent flow inside a hydraulically smooth circular duct. Using the flowrate equation  $\dot{w} = 144 \rho AV$ , the Reynolds number based on the tube inside diameter is

$$N_{Re} = \frac{144 \dot{w}}{3\pi D\mu} , \quad (13)$$

and the friction factor is

$$f = .0014 + .125 N_{Re}^{-.32} . \quad (14)$$

This module is based upon the relationships for frictional flow in constant area ducts derived in Reference 2, Section 6.2. The Mach number at the inlet is

$$M_i = V / \sqrt{g_c \gamma R T_i} . \quad (15)$$

The exit Mach number  $M_o$  is evaluated by Newton-Raphson iteration of the following equation which was obtained from Reference 2, Equations 6.20 and 6.21:

$$48 \bar{f} \frac{L}{D} = \left[ \frac{1-M^2}{\gamma M^2} + \frac{\gamma+1}{2\gamma} \ln \left( \frac{(\gamma+1)M^2}{2(1+\frac{\gamma-1}{2} M^2)} \right) \right]_i - \quad (16)$$

$$\left[ \frac{1-M^2}{\gamma M^2} + \frac{\gamma+1}{2\gamma} \ln \left( \frac{(\gamma+1)M^2}{2(1+\frac{\gamma-1}{2} M^2)} \right) \right]_o . \quad (17)$$

The outlet conditions of the adiabatic line then become

$$P_o = P_i \frac{M_i}{M_o} \sqrt{\frac{1 + \frac{\gamma-1}{2} M_i^2}{1 + \frac{\gamma-1}{2} M_o^2}} , \quad (18)$$

$$P_{to} = P_o \left( 1 + \frac{\gamma-1}{2} M_o^2 \right)^{\frac{\gamma}{\gamma-1}} , \quad (19)$$

$$T_{to} = T_{ti} , \quad (20)$$

and 
$$T_o = T_i \left( \frac{1 + \frac{\gamma-1}{2} M_i^2}{1 + \frac{\gamma-1}{2} M_o^2} \right) . \quad (21)$$

Isothermal Line - In problems involving transporting gases over long distances in uninsulated ducts exposed to a constant temperature environment, an assumption of isothermal flow with friction is sometimes justified. The resulting formulation is the basis of the isothermal line module. Here, the Reynolds number and friction factor are evaluated as in the adiabatic line (Equations 13 and 14). The line exit pressure  $P_o$  is evaluated by a Newton-Raphson iteration of the relation (Reference 2, Equations 6.42 and 6.44):

$$P_i^2 - P_o^2 = .100723 \frac{\dot{w}^2 T_i R}{D^4} \left( 24 \frac{fL}{D} - \ln \frac{P_o}{P_i} \right) . \quad (22)$$

The other outlet conditions are

$$T_o = T_i, \quad (23)$$

$$P_{to} = P_o \left(1 + \frac{\gamma-1}{2} M_o^2\right)^{\frac{\gamma}{\gamma-1}}, \quad (24)$$

and  $T_{to} = T_o \left(1 + \frac{\gamma-1}{2} M_o^2\right), \quad (25)$

where  $M_i = V/\sqrt{g\gamma RT_i}, \quad (26)$

and  $M_o = M_i (P_i/P_o). \quad (27)$

Gas Lines With Friction and Heat Transfer - The most general gas line module considers both friction and heat transfer due to radiation and natural convection. Considerably more specification data is required including environmental fluid properties. Since conditions may vary considerably along the flow path, the line is broken into a number of segments, each having a uniform wall temperature. Friction and heat transfer are evaluated at each segment and the effects are added from one segment to the next. The following relationships apply over a segment of length  $\Delta X = L/n$  where  $n$  is the number of segments.

Assuming the wall temperature is approximately equal to the gas stagnation temperature ( $T_w \approx T_t$ ), the exterior Grashoff number evaluated with environmental fluid properties is given by:

$$N_{Gr} = \frac{\rho_E^2 (T_E - T_t) D_E^3}{1728 T_E \mu_E^2}. \quad (28)$$

The Prandtl number of the environmental fluid is an input constant so that the external heat transfer coefficient due to free convection is obtained from the correlation function (Reference 3, Equation 7-28):

$$H_o = .53 K_E (N_{Gr} N_{Pr})^{.25} (12/D_o). \quad (29)$$

The inner wall heat transfer coefficient is evaluated from a correlation function applicable for turbulent forced convection which is

$$H_i = .023 (12/D) K N_{Re}^{.8} N_{Pr}^{.4} \quad (30)$$

The wall temperature and the radiation equivalent heat transfer coefficient are obtained by iterating two times on the following equations:

$$T_W = \frac{(H_o + H_R) T_E + H_i T_t}{(H_o + H_R + H_i)} \quad (31)$$

$$\text{and } H_R = .1714 \times 10^{-8} \epsilon (T_E + T_W) (T_E^2 + T_W^2) \quad (32)$$

where  $\epsilon$  is the wall emissivity.

The overall effective heat transfer coefficients then may be written as

$$H_{eff} = \left[ \frac{1}{(H_o + H_R) A_o} + \frac{1}{H_i A_i} + \frac{A_K}{K_W} \right]^{-1} \quad (33)$$

where  $A_i$  and  $A_o$  are the wall inside and outside surface areas

$$A_i = \pi D_i \Delta X / 12, \quad (34)$$

$$A_o = \pi (D_i + 2th) \Delta X / 12, \quad (35)$$

and  $A_K/K_W$  is the thermal resistance of a hollow circular cylinder defined by

$$\frac{A_K}{K_W} = \frac{\ln(D_o/D_i)}{2\pi\Delta X K_W} \quad (\text{Reference 3, Equation 2-8}) \quad (36)$$

Assuming the wall temperature is approximately constant over the segment  $\Delta X$ , the total temperature at the end of the segment ( $T_{tB}$ ) relative to the temperature at the beginning ( $T_{tA}$ ) is computed as

$$T_{tB} = T_E - (T_E - T_{tA}) \exp \left[ \frac{-0.16 H_E}{\pi \rho D^2 V C_p} \right]. \quad (37)$$

The local Reynolds number and friction factor are obtained from Equations (13) and (14).

The Mach number sensitivity to temperature change and friction is (Reference 2, Equation 8.53)

$$dM^2 = F_1 \frac{dT_t}{T_t} + F_2 48 \frac{dX}{D} \quad (38)$$

where  $F_1$  and  $F_2$  are the influence coefficients defined by

$$F_1 = \frac{M^2 (1 + \gamma M^2) (1 + \frac{\gamma-1}{2} M^2)}{1 - M^2} \quad (39)$$

$$\text{and } F_2 = \frac{\gamma M^4 (1 + \frac{\gamma-1}{2} M^2)}{1 - M^2} \quad (40)$$

Upon integrating Equation (38) over the length  $\Delta X$  and using conditions at the beginning and end of the segment, the following equation for the end Mach number  $M_B$  is obtained (Reference 2, Equation 8.55):

$$M_B^2 = M_A^2 + \left[ \frac{2\bar{F}_1}{\left(\frac{T_{tB}}{T_{tA}} + 1\right)} + \frac{\bar{F}_2 48f \Delta X/D}{\left(\frac{T_{tB}}{T_{tA}} - 1\right)} \right] \left( \frac{T_{tB}}{T_{tA}} - 1 \right) \quad (41)$$

$\bar{F}_1$  and  $\bar{F}_2$  are mean values evaluated at the average Mach number

$$\bar{M} = \frac{1}{2} (M_A + M_B). \quad (42)$$

Newton-Raphson iteration of Equations (39) through (42) is used.

Having obtained the total temperature and Mach number at the segment end, the other conditions are computed using ideal gas equations similar

to Equations (18), (19), and (21). These segment end conditions become the beginning conditions at the next line segment. The computation described above is repeated for each succeeding line segment until the end of the line is reached. The outlet conditions of the line include values of  $P_t$ ,  $T_t$ ,  $P$ ,  $T$ ,  $\dot{w}$ ,  $\rho$ ,  $C_p$ , and  $\gamma$ .

Liquid Line With Heat Transfer and Friction - The general liquid line module considers heat transfer, friction, and elevation changes. The line outlet conditions are evaluated directly in terms of the inlet conditions.

The overall heat transfer coefficient is evaluated in the same way as described above for the general gas line. The exit temperature is given by

$$T_o = T_i + \frac{H_{eff}(T_E - T_i)}{3600 \dot{w} C_v} + \frac{48 f L}{D} \frac{V^2}{2g_c C_v 778.26} \quad (43)$$

Using  $g$  for the local acceleration and  $\alpha$  for the angle down from horizontal, the line discharge pressure is given by

$$P_o = P_i + \frac{\rho g L \sin \alpha}{g_c 144} - 48 f \frac{L}{D} \frac{144 \rho V^2}{g_c} \quad (44)$$

For design purposes, the line diameter or length may be designated as a state variable. Optional design constraints associated with the line modules include a design pressure drop down the line,  $\Delta P_D$ , and the line outlet boundary pressure,  $P_{oD}$ .

These constraints are implemented as

$$f = 1 - (P_i - P_o) / \Delta P_D \quad (45)$$

$$\text{and} \quad f = 1 - P_o / P_{oD} \quad (46)$$

## 4.2 Junction

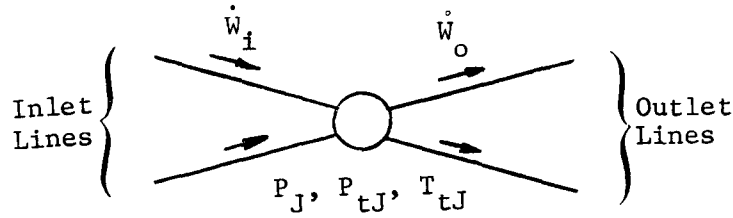


Figure 4.1 Junction Schematic

The junction module (JUNCL) provides a means of combining the flow from several inlet lines and/or splitting the flow into several outlet lines. Any combination of as many as 5 inlet and 5 outlet lines may be specified. The fluid in the lines connected by a junction may be either liquid or gas. Mixing of different fluids or of liquid and gaseous phases is not permitted. However, the entering streams may be of differing temperatures. All necessary fluid properties are obtained from the outlet locations of the upstream lines. These include  $\dot{W}$ ,  $P$ ,  $P_t$ ,  $T_t$ , and  $C_p$ . In the following development, several incoming ( $N_i$ ) and several outgoing ( $N_o$ ) lines are assumed. The equations continue to apply for  $N_i=1$  and  $N_o=1$ .

A primary balance which must be satisfied at a junction is the conservation of mass. The flowrates in the inlet lines are available from prior execution of the upstream line modules. (The user may also load the necessary values into the line module output locations thereby providing a constant inlet boundary condition to the junction. If this is done, the line module need not be executed.) However, there is no basis for specifying the flow division among the outlet lines. For this reason, the flowrates of all junction outlet lines must be designated as state variables and assigned initial estimates. With these estimates, the junction mass balance constraint equation is

$$0 = \sum_{i=1}^{N_i} \dot{W}_i - \sum_{o=1}^{N_o} \dot{W}_o \quad (1)$$

Since the flowrate may be zero in all the lines, the non-zero reference quantity used for normalizing the constraint is defined as the sum of the inlet and outlet flowrates evaluated at the first iteration. The normalized flowrate constraint function then is defined as

$$f = \left[ \sum \dot{W}_i - \sum \dot{W}_o \right] / \left[ \sum \dot{W}_i + \sum \dot{W}_o \right]_{\text{initial}}, \quad (2)$$

where the summations extend over  $N_i$  and  $N_o$  as appropriate.

The junction pressure is defined as a simple average of the inlet pressures

$$P_J = \frac{1}{N_i} \sum P_i \quad (3)$$

For pressure continuity at the junction, the pressures at the ends of the inlet lines are constrained to a common value. To accomplish this,  $N_i - 1$  pressure constraints of the form

$$f = 1 - P_i / P_J \quad (4)$$

are imposed. (Note that for  $N_i = 1$ ,  $P_J = P_i$  and the pressure continuity requirement is satisfied identically. Hence, imposition of a pressure constraint for one inlet is not necessary.) This definition of pressure continuity basically assumes zero dynamic pressure recovery as the streams enter the junction. This assumption is standard and is reasonably accurate for moderate entrance velocities. The alternative of assuming 100% total pressure recovery implies the reduction of the flow velocities to zero by isentropic diffusers. A rigorous derivation of the junction pressure would require a detailed specification of the junction geometry (flow areas, entrance angles, etc.) and consideration of the non-isentropic mixing process.

Assuming the junction is adiabatic and the fluid specific heat is constant, the total temperature of the fluid in the junction is given exactly by the equation

$$T_{tJ} = \frac{\sum \dot{W} C_P T_{ti}}{\sum \dot{W} C_P} . \quad (5)$$



The total pressure is defined as the mass-weighted average of the inlet total pressures

$$P_{tJ} = \frac{\sum \dot{W} P_{ti}}{\sum \dot{W}} \quad (6)$$

Assuming no line entrance losses, the junction pressure and temperature are loaded into the input locations of the lines attached to the junction outlets:

$$P_{ti} = P_{tJ} \quad (7)$$

$$T_{ti} = T_{tJ} \quad (8)$$

As a check on the validity of the junction formulation it is noted that the degenerate case of a junction having one inlet line and one outlet line (of the same diameter) produces no effect and is equivalent to a single line without a junction.

The feedback module used for closed-loop flow paths is associated directly with the junction (Section 3.4). When a feedback loop is specified by input, execution of the feedback module is controlled automatically by the junction module.

#### 4.3 Choked Exit

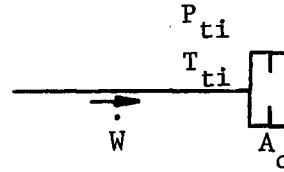


Figure 4.2 Choked Exit Schematic

Sonic conditions exist at the end of a gas line which empties into a vacuum or an atmosphere having a pressure below about 0.54 times the line total pressure. Under these conditions, a specific relationship existing between the gas pressure, flowrate, flow area and fluid properties must be satisfied. Assuming constant properties of a perfect gas, the choking flowrate is specified by

$$\dot{W}_c = P_t A_c \sqrt{\frac{g_c \gamma}{RT_t} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}}$$

where  $P_t$  and  $T_t$  are the total pressure and temperature and  $A_c$  is choking area. The constraint imposed on the exit flowrate ( $\dot{W}$ ) then becomes

$$f = 1 - \dot{W}/\dot{W}_c \quad (2)$$

Typically, the equation solver would adjust upstream state variables which influence  $P_t$ ,  $T_t$ , and  $\dot{W}$  in order to effect this balance. However, for design purposes, the choking area may be specified as a state variable, in which case the exit orifice would be sized to satisfy the constraint.

#### 4.4 Storage Tank/Accumulator

The TANK module was developed to model a general pressure vessel which may be a gas-pressurized liquid propellant tank, a gas accumulator, or a surge damper. The basic function of this module is to provide the time-dependent pressure boundaries associated with a component containing a trapped gas volume. The gas pressure is computed from the ideal gas equation of state using the integrals of mass, volume, and heating rates. Mean gas properties are computed when two gaseous species co-exist in the volume. The tank schematic shows the various possible inlet and outlet ports and the heat input.

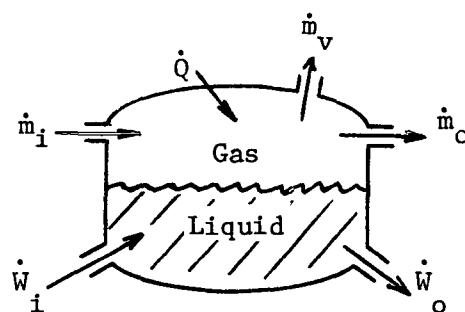


Figure 4.3 Tank Schematic

The flow and heating rates indicated in the schematic are input to the component module. For a given component, only those rates which apply to that particular component need to be specified. All others are set to zero by the program. Similarly, the number of required initial conditions depends upon the component simulated.

Two gaseous species are considered to exist in the gas volume. The tank is prepressurized with a quantity of gas of species 1 computed from the specified initial pressure, temperature, and volume conditions. The pertinent gas properties must be provided as input. Gas of species 2 may be added to the gas volume at the flowrate  $\dot{m}_1$  to provide continuing pressurization.

At any given time, the quantities of both species ( $m_1$  and  $m_2$ ) present in the tank are known by integration of the flowrates. The total mass of gas is

$$m_t = m_1 + m_2 \quad (1)$$

The two species are assumed to be thoroughly mixed so that the composition of the gas mixture is uniform throughout the volume. The

proportion of species 2 in the mixture is:

$$\alpha = \frac{m_2}{m_1 + m_2} \quad (2)$$

The gas mixture may be withdrawn from the volume by specifying  $\dot{m}_o > 0$ . A vent valve is simulated which opens at the specified pressure,  $P_{vent}$ . The gas mixture vents at the choking flowrate:

$$\dot{m}_v = \frac{g_c A_v P f(\gamma)}{\sqrt{g_c \gamma R T}} \quad , \quad (3)$$

where  $f(\gamma)$  is the tabular function

$$f(\gamma) = \gamma \left( \frac{2}{\gamma+1} \right)^{\frac{1}{2} \left( \frac{\gamma+1}{\gamma-1} \right)}$$

The net rates of change of the two gas species are given by

$$\dot{m}_1 = (\alpha - 1) (\dot{m}_o + \dot{m}_v) \quad \text{and} \quad (4)$$

$$\dot{m}_2 = \dot{m}_1 - \alpha(\dot{m}_o + \dot{m}_v). \quad (5)$$

Updated gas quantities are obtained by numerical integration of the rates. Specifically, the trapezoidal rule is employed so that:

$$m_1^{n+1} = m_1^n + 1/2 (\dot{m}_1^n + \dot{m}_1^{n+1}) \Delta t \quad (6)$$

$$m_2^{n+1} = m_2^n + 1/2 (\dot{m}_2^n + \dot{m}_2^{n+1}) \Delta t \quad (7)$$

The net rate of change of liquid in the tank is

$$\dot{W}_n = \dot{W}_i - \dot{W}_o, \quad (8)$$

and the integrated liquid weight is

$$W_n^{n+1} = W_n^n + 1/2 (\dot{W}_n^n + \dot{W}_n^{n+1}) \Delta t \quad (9)$$

If  $V_t$  is the total tank volume, and  $\rho_L$  is the liquid density, the remaining volume occupied by the gas is

$$V_g = V_t - \frac{W}{\rho_L} \quad (10)$$

For a mixture of two calorically perfect gases, the effective gas properties are given by

$$\bar{R} = (R_1 m_1 + R_2 m_2) / m_t, \quad (11)$$

$$\bar{C}_p = (Cp_1 m_1 + Cp_2 m_2) / m_t, \quad (12)$$

$$\bar{C}_v = \bar{C}_p - R \quad 778.16, \quad (13)$$

$$\text{and } \bar{\gamma} = \bar{C}_p / \bar{C}_v. \quad (14)$$

The rate of change of the enthalpy from the incoming gas is

$$\dot{h}_i = \dot{m}_i C_{p2} T_i, \quad (15)$$

and the rate of change of the enthalpy from the gas mixture leaving the volume is

$$\dot{h}_o = \dot{m}_o \bar{C}_p \bar{T}, \quad (16)$$

$$\text{and } \dot{h}_v = \dot{m}_v \bar{C}_p \bar{T}. \quad (17)$$

Work is performed on the gas by movement of the liquid surface at the rate

$$\dot{W} = P \dot{W}_n / \rho_L \left( \frac{144}{778} \right). \quad (18)$$

By the first law, the rate of change of internal energy in the open system shown in Figure 4.3 is

$$\dot{u} = \dot{Q} + \dot{h}_i - \dot{h}_o - \dot{h}_v + \dot{W}. \quad (19)$$

The integrated internal energy is computed as

$$u^{n+1} = u^n + 1/2 (\dot{u}^n + \dot{u}^{n+1}) \Delta t. \quad (20)$$

Using the updated quantities the average temperature of the gas mixture (tank temperature) is given by

$$T_{\text{tank}} = \frac{u}{m_t \bar{C}_v}. \quad (21)$$

Assuming the gas mixture to be thermally perfect, the tank pressure is obtained from the equation of state:

$$P_{\text{tank}} = m_t \bar{R} T_{\text{tank}} / (V_g 144). \quad (22)$$

For pressure continuity, the static pressures at the outlet ends of the two incoming lines (liquid and gas) are constrained to equal the tank pressure by a constraint of the form

$$f = 1 - P_o / P_{\text{tank}}. \quad (23)$$

This constraint assumes a sudden expansion as the incoming fluid enters the tank and implies zero dynamic pressure recovery.

If liquid or gas outlet lines are connected to the tank the following conditions are transferred to the line inlets:

$$P_{ti} = P_{\text{tank}}, \quad (24)$$

$$T_{ti} = T_{\text{tank}}. \quad (25)$$

Equation (24) neglects entrance losses.

The tank component module is the only one containing a time dependence. To satisfy the assumption of quasi-steady state operating conditions, the pressure changes in the tank should occur slowly relative to the response rates of other components in a system.

#### 4.5 Valve/Orifice

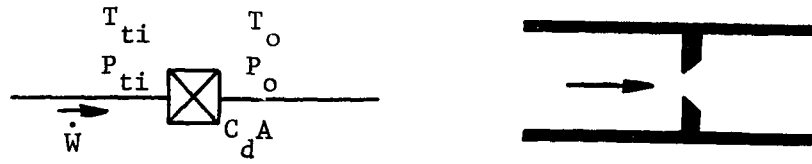


Figure 4.4

Valve/Orifice Schematic

Simplified Orifice

The pressure drop across valves and orifices is modeled by the valve module which employs the basic orifice equations for compressible and incompressible fluids. The pressure drop across injector orifices associated with the combustion chamber is evaluated by an internal reference to the valve module by the chamber module.

The orifice is characterized by an effective flow area  $C_d A$  which is the product of the discharge coefficient and the actual flow area. For design purpose,  $C_d A$  may be designated a state variable.

Two distinct modules are provided, one for liquids (VALVL) and one for gases (VALVG). The outlet pressure for the liquid valve is computed directly from the fluid properties at the inlet according to the equation

$$P_o = P_i - \frac{144}{2 \rho_i g_c} \left( \frac{\dot{W}}{C_d A} \right)^2. \quad (1)$$

The orifice equation for an unchoked perfect gas is (Reference 4, Equation 3.13)

$$\dot{W} = P_{ti} C_d A \sqrt{\frac{g_c}{RT_{ti}}} \left( \frac{2\gamma}{\gamma-1} \right) \left[ \left( \frac{P_o}{P_{ti}} \right)^{\frac{2}{\gamma}} - \left( \frac{P_o}{P_{ti}} \right)^{\frac{\gamma+1}{\gamma}} \right]. \quad (2)$$

This equation is implicit in the desired outlet pressure  $P_o$ , the other parameters being known from inlet conditions and the specified flow area,  $C_d A$ .  $P_o$  is evaluated iteratively from this equation using the Secant method. Since  $P_o/P_{ti}$  must be less than 1.0 from both physical and computational considerations, this ratio is limited by the relation

$$\frac{P_o}{P_{ti}} \leq 1 - \left( \frac{1}{10} \right)^n, \quad (3)$$



where  $n$  is the current iteration counter between 1 and 20.

The lower limit is the critical pressure ratio which produces choking, given for an ideal gas by the relation (Reference 4, Equation 3.14):

$$\left. \frac{P_o}{P_{ti}} \right|_{\text{crit}} = \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma}{\gamma-1}}. \quad (4)$$

In the event the valve flow area is specified too small for the flow conditions required, the assumption of subsonic flow may not be satisfied. In this contingency, the outlet pressure will be defined by Equation (4) and an error diagnostic will be printed.

For design purposes, with either valve module, the user may specify a desired pressure drop,  $\Delta P_D$ . The constraint generated is of the form

$$f = 1 - (P_i - P_o) / \Delta P_D. \quad (5)$$

An additional capability to model the operation of a check valve has been incorporated into both valve modules. A checked flow is indicated whenever the flowrate through the valve is negative, a condition used solely for computational purposes. When this occurs, the valve performs the same calculations using the absolute value of the flowrate. However, the computed pressure drop becomes a pressure rise added to the inlet pressure. In this way downstream constraint equations relying on the valve back pressure continue to vary smoothly and can be satisfied.

#### 4.6 Pressure Regulator

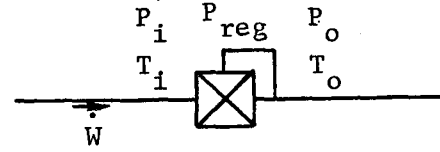


Figure 4.5 Pressure Regulator Schematic

The pressure regulator maintains a constant downstream pressure ( $P_o$ ) which is independent of the upstream pressure ( $P_i$ ) as long as  $P_i > P_{reg}$ . The outlet pressure is defined as

$$P_o = P_{reg} \text{ for } P_i \geq P_{reg}, \quad (1)$$

$$\text{and } P_o = P_i \text{ for } P_i < P_{reg}. \quad (2)$$

The regulator is modeled as an isenthalpic throttling valve. The fluid temperature at the regulator outlet ( $T_o$ ) is defined as follows. For liquids and for gases which can be considered ideal, the temperature remains constant so that

$$T_o = T_i. \quad (3)$$

For fluids in the vicinity of the critical point, the assumptions of ideal gas or incompressible liquid cannot be made with accuracy. Letting  $h$  represent the enthalpy functions evaluated by the thermodynamic property sub-routines, the constant enthalpy process implies

$$h(T_i, P_i) = h(T_o, P_o). \quad (4)$$

The parameters  $T_i$ ,  $P_i$ , and  $P_o$  are known so that  $T_o$  is evaluated iteratively using the Secant Method. Hydrogen and oxygen are the only fluids considered here which may be near the critical point. For simplicity, the constant enthalpy process is imposed rigorously for hydrogen and oxygen regardless of the proximity to the critical point.

For design purposes, the regulator pressure,  $P_{reg}$  may be specified as state variable.

#### 4.7 Thrust Chamber/Gas Generator

The chamber module (CHAM) characterizes the performance of thrust chambers and gas generators. The basic module consists of a chamber and two equivalent injector orifices through which the incoming propellants enter. The module is designed to operate with either a monopropellant or bipropellants. When operating with a monopropellant, only the first injector is used. As a thrust chamber, the combustor is coupled to an exhaust nozzle, and thrust calculations based upon theoretical nozzle  $C_f$  are performed. Choking conditions at the nozzle throat are imposed. When operating as a gas generator, the exit flow is not choked, and the chamber pressure depends upon downstream conditions. The two types of chambers are shown in Figure 4.6. Each may operate with either monopropellant or bipropellants.

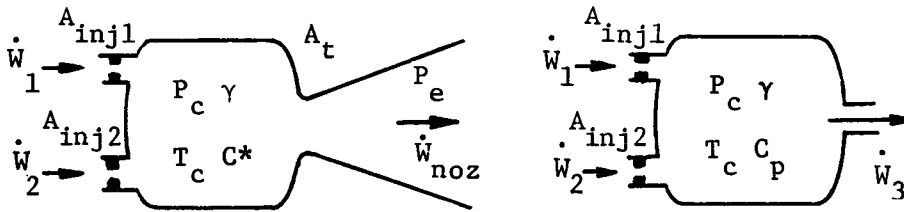


Figure 4.6 Combustion Chamber Schematic

Input data consist of the total pressure, total temperature, flowrate, and fluid properties obtained from the upstream lines connected to the injector inlets. The pressure downstream of the injector is obtained from the appropriate liquid or unchoked gas orifice equations (See Section 4.5).

For a bipropellant combustor, the two pressures downstream of the respective injectors are constrained to a common value. The two chamber pressures based upon flow are designated as  $P_{cw1}$  and  $P_{cw2}$ . The bipropellant pressure constraint is

$$f = 1 - P_{cw2}/P_{cw1}. \quad (1)$$

The oxidizer/fuel mixture ratio is defined as

$$MR = \dot{W}_1/\dot{W}_2 \text{ or } MR = \dot{W}_2/\dot{W}_1 \quad (2)$$

depending upon the type of propellant entering injector 2.

At this point, the combustor characterization is obtained from three-dimensional tabular functions of the independent variables mixture ratio and pressure. The value of the chamber pressure used to enter these tables is defined by either  $P_{cw} = P_{cw1}$  or  $P_{cw} = 1/2 (P_{cw1} + P_{cw2})$  depending upon whether one or two propellants are used. For the hydrazine characterization tables, the fraction of  $NH_3$  dissociated is used in place of the mixture ratio.

$C^*$  Theoretical characteristic exhaust velocity

$T_c$  Combustion temperature

$C_p$  Specific heat

$\gamma$  Specific heat ratio

Data tables of these functions exist for the following propellant combinations:  $H_2/O_2$ , A-50/ $N_2O_4$ , and hydrazine monopropellant. Sources and plots of these data may be found in Section 6.0 (Combustion Characterization).

The  $C^*$  data are used with the thrust chamber option, and represent the theoretical values at the given mixture ratios and chamber pressure. Due to imperfect mixing and combustion and real gas effects, the actual  $C^*$  delivered by a combustion chamber is given by

$$C^*_{\text{actual}} = \eta_c^* \cdot C^* \quad (3)$$

where  $\eta_c^*$  is the  $C^*$  efficiency which typically is close to one.

For a thrust chamber, the choking conditions at the nozzle throat isolate the chamber from the downstream conditions and chamber pressure is computed by:

$$P_c = \frac{\dot{W}_{\text{noz}} \cdot \eta_c^* C^*}{g_c A_t} \quad (4)$$

This pressure and the flow pressure,  $P_{cw}$ , are forced to be equal by imposing the constraint function

$$f = 1 - P_c / P_{cw} \quad (5)$$

For the gas generator, Equations (3), (4), and (5) do not apply. The interim chamber pressure is defined by the flow pressure ( $P_c = P_{cw}$ ) and all necessary gas properties are loaded into the discharge line. The balanced chamber pressure depends upon downstream conditions, and it is necessary to delay imposing a constraint until a balance is required at some downstream location; typically this would be a choked-flow balance in a turbine or at an exit to the atmosphere, or a pressure balance at a junction or pressure boundary.

As a design option, it is possible to specify a required chamber pressure in which case the following constraint is imposed

$$f = 1 - P_c / P_{cD}. \quad (6)$$

When modeling a liquid rocket engine, the following additional relations are employed. The combustion products are assumed to be a non-reacting ideal gas having a constant specific heat ratio. The gas expands isentropically through a conical nozzle from the stagnation conditions in the combustion chamber. Given the gas properties and the nozzle expansion ratio ( $\epsilon$ ), the exit-plane pressure is evaluated iteratively from the following equation (Reference 5, Equation 3-25):

$$\frac{1}{\epsilon} = \frac{A_t}{A_e} = \left(\frac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}} \left(\frac{P_e}{P_c}\right)^{\frac{1}{\gamma}} \sqrt{\frac{\gamma+1}{\gamma-1} \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}. \quad (7)$$

The thrust coefficient for optimal expansion is obtained from

$$C_{f \text{ opt}} = \sqrt{\frac{2\gamma}{\gamma-1} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}. \quad (8)$$

(Reference 5, Equation 3-30)

To account for various losses occurring in the nozzle, an efficiency,  $\eta_{Cf}$ , has been introduced. The divergence loss is accounted for by the factor  $\lambda$ . The effective thrust coefficient, considering these losses and non-optimal expansion, is computed as

$$C_f = \lambda \eta_{Cf} C_{f \text{ opt}} + \frac{\epsilon}{P_c A_t} (P_e - P_{\text{atm}}) \quad (9)$$

The resulting thrust and specific impulse become.

$$F = C_f P_c A_t \quad (10)$$

$$\text{and } I_{sp} = \frac{F}{\dot{W}_{noz}} \quad (11)$$

For design purposes, a required mixture ratio and either thrust or specific impulse can be specified in which case one or more of the following constraints will be imposed:

$$f = 1 - MR/MR_D, \quad (12)$$

$$f = 1 - F/F_D, \quad (13)$$

$$\text{and } f = 1 - I_{sp}/I_{spD} \quad (14)$$

} either, but not both

Care should be exercised when specifying additional chamber constraints to assure a sufficient number of state variables to yield a determinate system of equations.

It should be noted that as formulated, this model is quite general and applies to any liquid rocket engine or gas generator. The necessary characterization data refer only to the propellants used and are not restricted to a specific piece of hardware. Considerable flexibility has been built into the chamber module. Four optional design constraints are available. The required state variables can be selected from the following list: injector flowrates (2), injector areas (2), nozzle throat area, and expansion ratio.

#### 4.8 Gas Turbine

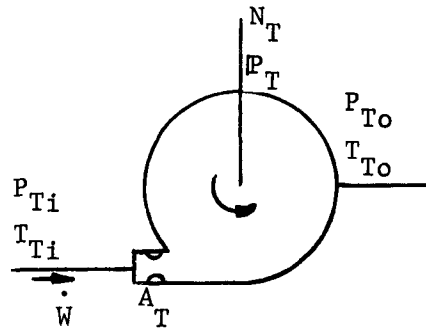


Figure 4.7 Gas Turbine Schematic

A gas turbine converts the enthalpy at a gas stream into shaft work to drive various components such as centrifugal pumps and electrical power units. The turbine module in this program can be driven by a gas generator or a tank of compressed gas. In the turbine module designed for the present system, the gas stream is choked at the throat of an inlet nozzle or in the stator blades depending upon the type of turbine being considered. From here the gas passes through the rotor blades from which the power is extracted.

This turbine is characterized by an effective choking area ( $A_T$ ), the rotor tip diameter ( $D_T$ ), and an overall turbine efficiency ( $\eta_T$ ) which varies with the ratio of tip speed to isentropic spouting velocity ( $u/C$ ).

The turbine exhaust may empty directly into the atmosphere, in which case the back pressure ( $P_o$ ) is a known quantity. Or, the turbine outlet may be connected to gas line, in which case the back pressure depends upon the downstream conditions and must be obtained through the balance of the system equations. To do so,  $P_o$  is designated as a state variable. An associated constraint equation then must be imposed at some downstream position. Typically this would be a pressure balance at a pressure boundary, or a flowrate constraint at a choking exit to the atmosphere. However, other constraining balances are possible if the turbine exhaust gases are used to drive a second turbine or a thrust chamber.

For turbines designed to operate with a choked flow at the inlet, the following relationship must be satisfied. Assuming isentropic expansion of a perfect gas, the choking flowrate, in terms of the inlet conditions is given (Reference 4, Equation 3.16) by:

$$\dot{W}_c = P_{ti} A_T \sqrt{\frac{g_c \gamma}{RT_{ti}}} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \quad (1)$$

The constraint on the inlet flowrate becomes

$$f = 1 - \dot{W}/\dot{W}_c \quad (2)$$

As discussed above, the outlet pressure is either an input constant or a state variable and, hence, during a given program iteration, has a specified value. For conciseness the following abbreviation is introduced

$$B = 1 - \left( \frac{P_o}{P_{ti}} \right)^{\frac{\gamma-1}{\gamma}} \quad (3)$$

The isentropic spouting velocity is given by

$$C = \sqrt{2g_c C_p T_{ti} B(778.156)} \quad (4)$$

The turbine rotational speed ( $N_T$ ) usually is designated as a state variable and is used to compute the rotor tip speed.

$$u = \frac{\pi D_t N_t}{(12)(60)} \quad (5)$$

The speed ratio ( $R = u/C$ ) determines the overall power conversion efficiency from an input characterization curve of the form

$$\eta_T = a_1 R + a_2 R^2 \quad (6)$$

The typical efficiency curve is a downward-facing parabola having a maximum in the range  $0.1 < R < 1.0$  corresponding to

$$R_{\max} = -\frac{a_1}{2a_2} \quad (7)$$

Due to physical considerations, the maximum tip speed is limited, and it is reasonable to impose the condition  $R \leq R_{\max}$  for computational stability (Reference 5, Figure 9-18).

The total temperature of the turbine exhaust gases is given by

$$T_{to} = T_{ti} (1 - \eta_T B), \quad (8)$$



and finally, the power generated by the turbine is (Reference 5, Equation 9-18):

$$P = \eta_T \dot{W}_c C_p T_{ti} B (778). \quad (9)$$

This represents the power delivered to the driven component. For a performance-type problem, turbine speed is the appropriate independent variable. State variables effecting turbine design are the turbine inlet nozzle effective area ( $A_T$ ), turbine rotor diameter ( $D_T$ ), and turbine outlet pressure ( $P_{To}$ ).

#### 4.9 Centrifugal Pump

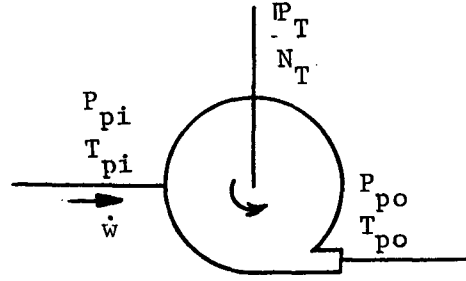


Figure 4.8 Pump Schematic

The pump module simulates a radial-flow centrifugal pump. Using similarity parameters, a pump having known performance characteristics may be scaled to a geometrically similar pump of different size.

Required characterization data consist of two polynomial curve fits of pressure rise and power required vs. flow rate at the design rotational speed ( $N_T$ ):

$$\Delta P_D = a_0 + a_1 \dot{w}_D + a_2 \dot{w}_D^2 \quad (1)$$

$$\text{and} \quad P_D = b_0 + b_1 \dot{w}_D + b_2 \dot{w}_D^2 + b_3 \dot{w}_D^3. \quad (2)$$

Other required input data consist of the driving turbine speed ( $N_T$ ), pump design speed ( $N_D$ ), applied power ( $P_T$ ), drive gear ratio ( $R_G$ ), impeller diameter ratio with respect to the design diameter ( $R_D = D_{\text{pump}}/D_{\text{design}}$ ), and the fluid variables ( $\dot{w}$ ,  $P$ ,  $T$ ,  $\rho$ ,  $C_p$ ). Being driven by a turbine operating at a prescribed speed, the pump rotational speed is  $N_P = N_T/R_G$  [RPM]. The speed ratio is defined as  $R_N = N_P/N_D$ .

Based upon Reference (6), the performance of geometrically similar pumps having similar flow patterns are related by the following similarity conditions:

$$\frac{\dot{w}_2}{\dot{w}_1} = \frac{N_2}{N_1} \left( \frac{D_2}{D_1} \right)^3, \quad (\text{Flowrate}) \quad (3)$$

$$\frac{\Delta P_2}{\Delta P_1} = \left( \frac{N_2}{N_1} \right)^2 \left( \frac{D_2}{D_1} \right)^2, \quad (\text{Pressure rise}) \quad (4)$$

$$\text{and} \quad \frac{P_2}{P_1} = \left( \frac{N_2}{N_1} \right)^3 \left( \frac{D_2}{D_1} \right)^5, \quad (\text{Power required}) \quad (5)$$

where the subscripts refer to two different pumps or to a single pump ( $D_2 = D_1$ ) operating at different speeds. Relating subscript (1) to the design conditions and the subscript (2) to the off design conditions, and using the speed and diameter ratios, these equations become

$$\dot{w} = \dot{w}_D (R_N R_D^3), \quad (6)$$

$$\Delta P = \Delta P_D (R_N^2 R_D^2), \quad (7)$$

$$\text{and} \quad P = P_D (R_N^3 R_D^5). \quad (8)$$

Combining equations (1) and (2) with (7) and (8), the pressure rise developed and the power required at the off-design conditions are given in terms of the performance characterization at design conditions by the following equations:

$$\Delta P_P = R_N^2 R_D^2 (a_0 + a_1 \dot{w}_D + a_2 \dot{w}_D^2) \quad (9)$$

$$\text{and} \quad P_P = R_N^3 R_D^5 (b_0 + b_1 \dot{w}_D + b_2 \dot{w}_D^2 + b_3 \dot{w}_D^3) \quad (10)$$

$$\text{where} \quad \dot{w}_D = \dot{w} / R_N R_D^3.$$

The pump power conversion efficiency is

$$\eta_p = \frac{144 \Delta P \dot{w}}{\rho P}. \quad (11)$$

The fluid temperature rise across the pump due to power dissipation in the form of heat entering the fluid is

$$\Delta T_P = \frac{(1-\eta_p) P}{778.16 \dot{w}_{C_P}}. \quad (12)$$

The pump output conditions become

$$P_{po} = P_{pi} + \Delta P_p \quad (13)$$

$$\text{and } T_{po} = T_{pi} + \Delta T_p \quad (14)$$

The power required to drive the pump ( $P_p$ ) depends only upon the pump characteristics, speed, and flowrate. This power obviously must match the power supplied by the driving turbine. To accomplish this, the constraint function

$$F = 1 - P_p / P_T \quad (15)$$

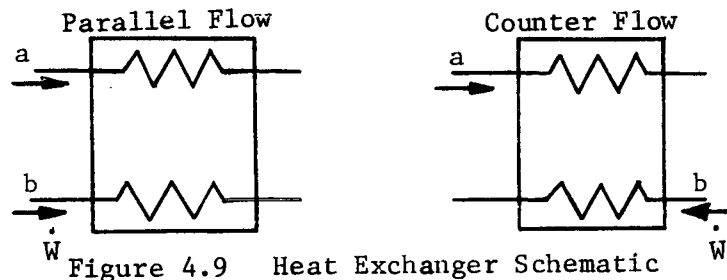
is formed automatically. For a performance analysis case, the turbine speed is designated as a state variable which permits the turbine/pump combination to seek the proper operating point. In the design mode, the turbine speed may be a specified constant in which case the power constraint might be achieved by sizing the turbine or the pump. An optional design constraint,

$$F = 1 - \Delta P_p / \Delta P_D \quad (16)$$

permits a specified pressure rise  $\Delta P_D$  to be imposed on the system solution.

The pump may be operated in the absence of a driving turbine if the turbine power ( $P_T$ ) and turbine speed ( $N_T$ ) are input by the user. It is further possible to specify one or both of these parameters as state variables, thus generating power and/or speed requirements. Additional design state variables are the drive gear ratio ( $R_G$ ) and the diameter ratio ( $R_D$ ).

#### 4.10 Heat Exchanger



A heat exchanger module was developed to model the performance of a heat exchanger operating under steady-state conditions. This program is equipped to analyze parallel and counter flow types of heat exchangers, and has the ability to simulate vaporization of the cold side fluid. A correlation for cross-flow heat exchangers has been included. The nominal heat exchanger consists of two concentric tubes, but optional input permits non-circular cross sections to be considered.

At the present time the thermodynamic properties of oxygen, hydrogen and their combustion products at a mixture ratio of 1.0 are included in the program. If hot combustion products are used, it is assumed that they flow through the outside tube (Side a). Boiling of a liquid (cryogenic hydrogen or oxygen) may take place in the inside tube (Side b).

The heat exchanger may be connected to any other component by a fluid line. For example, the hot-side gas can be obtained from a gas generator or from the outlet of a gas turbine. After passing through the heat exchanger, the hot-side gas normally is exhausted to the environment through a line terminating at a choked orifice.

The correlations defining the heat transfer film coefficients were specifically identified for oxygen and hydrogen. However, for other fluids, the temperature correction ( $T_w/T_b$ ) in the equations below can be set to unity. This reduces the correlations to the Dittus Boelter or Colburn form which can be used at moderate temperatures and pressures for all gases and liquids except liquid metals ( $P_r < 0.1$ ). Simulating heat exchanger performance with fluids other than hydrogen and oxygen will require the addition of the saturation enthalpies ( $h_L, h_G = \phi(T)$ ) if two-phase computations are required.

The heat exchanger discharge conditions are computed from the conditions of the inlet fluid streams. The outlet conditions for parallel flow types of heat exchangers are computed directly from the inlet conditions. For counter flow heat exchangers the discharge conditions are computed iteratively utilizing the Secant method.

The following basic equations are used in the heat exchanger model and are listed in the order of appearance. The nomenclature is defined in Section 9.0.

The Reynolds number is

$$N_{Re} = \frac{\dot{W} D_h}{\mu A} . \quad (1)$$

The hydraulic diameter is

$$D_h = \frac{4 A}{(\text{Wetted perimeter})} . \quad (2)$$

Any two of the three parameters in Equation (2) (hydraulic diameter, flow area, and wetted perimeter) may be used to specify the geometry if a heat exchanger being simulated is other than the concentric tube type.

This module is equipped to handle boiling heat transfer occurring in the inside tube. Thermodynamic properties necessary for this process have been incorporated for hydrogen and oxygen. If boiling occurs, it must result in the complete conversion from the liquid to the gaseous state. Various tests are performed to determine if the fluid has entered the two-phase region. The saturation temperature at the fluid inlet pressure is compared with the actual temperature. If the temperature is greater than the saturation temperature, the fluid has entered the two-phase region on a T-S diagram and calculation of the two-phase fluid enthalpy and quality is required. The enthalpy of the two-phase fluid is obtained from the saturated gas and liquid enthalpies by the relation

$$h = h_L + C_{pL} (T - T_{sat}) . \quad (3)$$

The enthalpy is then updated using:

$$h^{n+1} = h^n + dQ/\dot{W} . \quad (4)$$

A typical temperature-entropy diagram is shown in Figure 4.10. The quality of the fluid is defined in terms of the saturation enthalpies by the relation

$$X = \frac{h - h_L}{h_G - h_L} . \quad (5)$$

The thermal conductivity, viscosity, and Prandtl numbers are evaluated at the saturated gas conditions. The Martinelli parameter used for pressure correction due to two-phase momentum change is defined as

$$MART = \left( \frac{X}{1-X} \right)^{-.9} \left( \frac{\mu_G}{\mu_L} \right)^{-.1} \left( \frac{SV_G}{SV_L} \right)^{-.5} \quad (6)$$

The specific volume ( $1/\rho$ ) and specific heat of a two-phase fluid are defined as weighted averages of the saturation values:

$$SV = (X) SV_G + (1-X)SV_L \quad (7)$$

and 
$$C_p = (X) C_{pG} + (1-X)C_{pL} \quad (8)$$

The pressure drop correction term for two-phase flow is calculated as follows: (Reference 7, p.32)

$$P_{co} = \left[ 1 + MART^{.25} \left( \frac{1-X}{X} \right)^{.75} \left( \frac{\mu_L}{\mu_G} \right)^{.08} \left( \frac{SV_L}{SV_G} \right)^{.416} \right]^{2.4} \quad (9)$$

The Nusselt number for a turbulent fluid heat exchanger is evaluated using a correlation function of the form

$$N_{Nu} = f(N_{Re}, N_{pr}). \quad (10)$$

The heat transfer correlations used in the program are presented below. The boiling heat transfer correlation for hydrogen was derived from tests (Reference 7). However, no correlation for boiling heat transfer of oxygen was available. For this reason the oxygen boiling results should be considered approximate.

The heat transfer correlations used in the program include the following:

1. Hydrogen (Reference 8)

$$N_{Nu} = .023 N_{Re}^{.8} N_{Pr}^{.4} \left( \frac{T_w}{T_B} \right)^{-.55} f_1(T_B) \quad (11)$$

where  $f_1(T_B)$  is a correction for two-phase boiling.

2. Oxygen (Reference 3)

$$N_{Nu} = .023 N_{Re}^{.8} N_{Pr}^{.4} \left( \frac{T_w}{T_B} \right)^{-.34} f_2(T_B, T_w) \quad (12)$$

where  $f_2(T_B, T_w)$  is a correction for asymmetric heating.

3. Boiling Heat Transfer (Hydrogen and Oxygen) (Reference 7)

$$N_{Nu} = \frac{.023 N_{Re}^{.8} N_{Pr}^{.4}}{.611 + 1.93 \text{ MART}} \quad (13)$$

4. Crossflow correlation (Reference 9)

$$N_{Nu} = .3 F_n \frac{C_P \dot{W} D_h}{\gamma} N_{Re}^{-.4} N_{Pr}^{-.67} \left( \frac{T_B}{T_w} \right)^{.14} \quad (14)$$

where  $F_n$  is a correction depending upon the number of tube layers.

The heat transfer coefficients for the fluids are computed as follows

$$H = N_{Nu} \frac{K}{D_h} \quad (15)$$

Wall conductance is given by the relationship

$$H_w = \frac{K_w}{th} \quad (16)$$

Assuming the inside tube wall thickness is small ( $th \ll R_i$ ), the surface areas are approximately equal, and an equivalent heat transfer coefficient can be defined as

$$H_e = \frac{1}{\frac{1}{H_i} + \frac{1}{H_w} + \frac{1}{H_o}} \quad (17)$$

When operating in steady-state, the thermal capacitance of the wall is not applicable. Assuming negligible heat conduction in the axial



direction, the heat flux from the outside fluid to the inside fluid is

$$q = H_e (T_o - T_i) . \quad (18)$$

The temperature change of the single phase fluid over the incremental distance  $\Delta X$  is then computed as

$$T_{n+1} = T_n + \frac{qS}{\dot{W}C_p} \quad (19)$$

where  $S = 2\pi R \Delta X$ , and  $\bar{C}_p$  is the average specific heat.

If the fluid is boiling, the temperature is set equal to the fluid saturation temperature evaluated at the local pressure.

The pressure change through the heat exchanger results from momentum change and friction. The friction factor is given by

$$f = .0014 + .125 N_{Re}^{-.32} , \quad (20)$$

and the pressure drop is given by

$$\Delta P = \left( \frac{\dot{W}}{A} \right)^2 \frac{1}{g_c} \left( \Delta S V + 2f \bar{S} V \frac{\Delta X}{D_H} \right) . \quad (21)$$

If the fluid is two-phase the pressure drop correction term  $P_{co}$  is applied to the friction loss term resulting in

$$\Delta P = \left( \frac{\dot{W}}{A} \right)^2 \frac{1}{g_c} \left( S V + 2f P_{co} \bar{S} V \frac{\Delta X}{D_H} \right) . \quad (22)$$

Equation (22) is used to adjust the pressure as the fluid travels through the exchanger. As shown in Figure 4.10, the pressure is determined from one computation interval to the next by using an incremental pressure drop. With the new pressure at each step, a new saturation temperature is determined and used for the next computation. This is continued throughout the two-phase region.

The state variables which can be used in designing a heat exchanger are the radii of the inside and outside flow passages ( $R_{HXi}$  and  $R_{HXo}$ ) and the tube length ( $L_{HX}$ ). The optional design constraints available are the outlet temperatures of the two heat exchanger sides, imposed by

$$f = 1 - T_{ao}/T_{HXa} \quad (18)$$

and  $f = 1 - T_{bo}/T_{HXb}$ . (19)

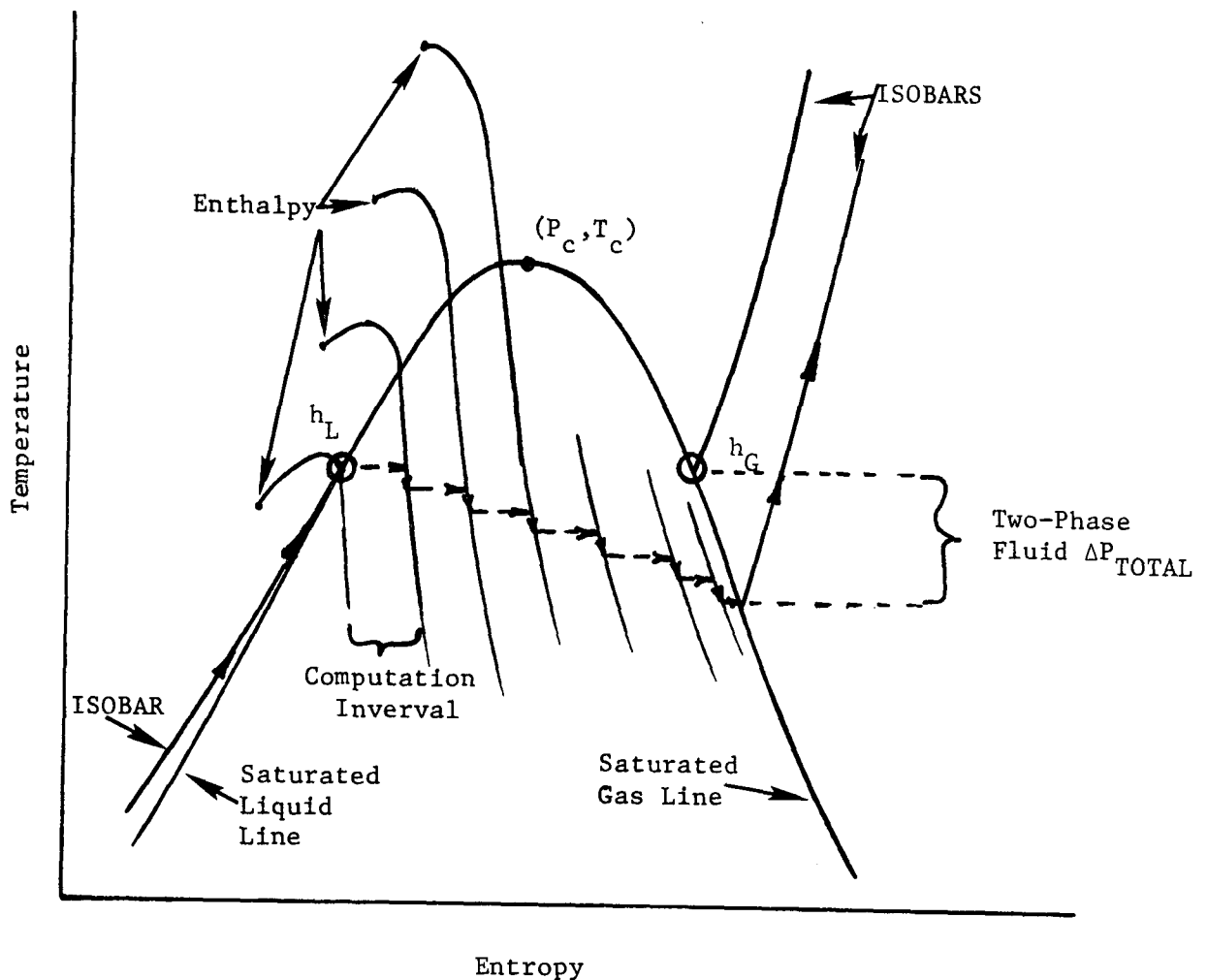


Figure 4.10 TYPICAL T-S DIAGRAM

## 5.0 FLUID PROPERTIES

Thermodynamic properties of the working fluid are required in many of the program calculations. The necessary fluid properties include density ( $\rho$ ), thermal conductivity (K), viscosity ( $\mu$ ), enthalpy (h), and the specific heat ( $C_p$ ).

### Hydrogen

All hydrogen properties are obtained directly from accepted NBS hydrogen property subroutines (Reference 10). These subroutines apply for pressures from 1 to 5000 psi and temperatures from 25 to 5000°R as shown in Figure 5.1.

### Oxygen

Oxygen properties are obtained from previously existing subroutines which employ property data from References 11 and 12. The data tables in the original subroutines were extended to increase the pressure range. The data presently covers the pressure range from 14.7 to 1249 psi and the temperature range from 144 to 540°R as shown in Figure 5.2. Since the pressure and temperature range is more restrictive for oxygen than for hydrogen, the oxygen subroutines were further modified to use the closest available data in the event that the pressure or temperature fell outside the permissible range. However, the out-of-range density value is computed from the perfect gas equation if the pressure is out of range-low or if the temperature is out of range-high. Diagnostics are printed whenever the input pressure or temperature is out of range.

Figure 5.1 HYDROGEN PROPERTY DATA RANGE

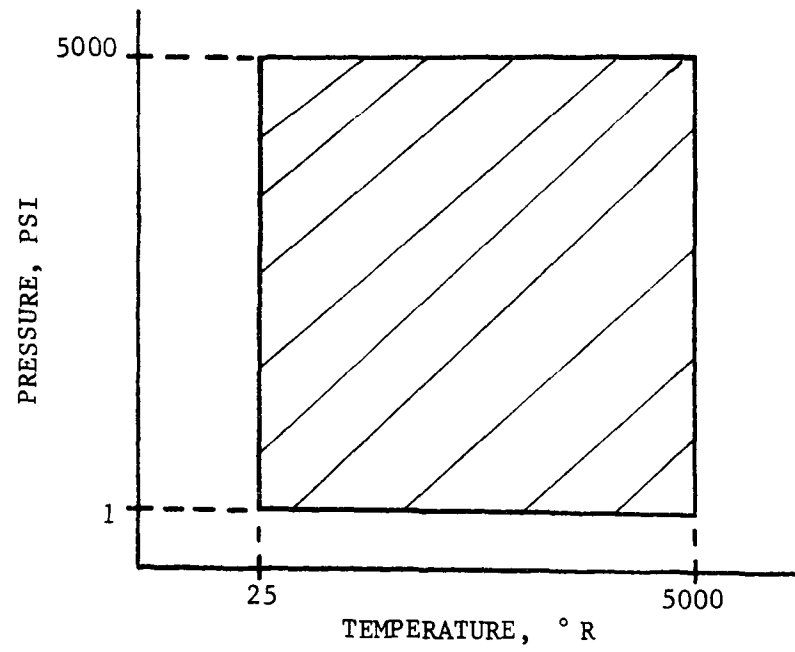
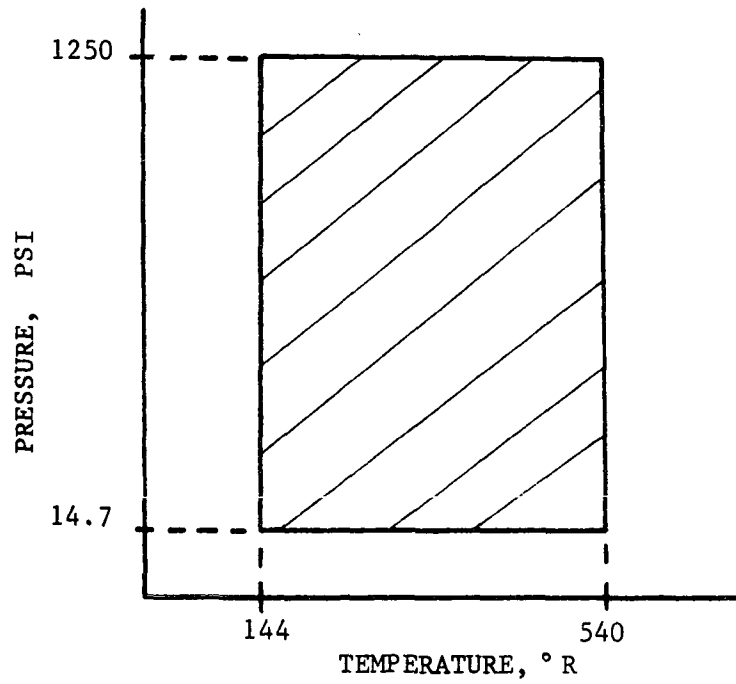


Figure 5.2 OXYGEN PROPERTY DATA RANGE



### Nitrogen Tetroxide ( $N_2O_4$ )

The fluid properties of  $N_2O_4$  in the liquid state are evaluated according to the following functions which are employed in the Apollo trajectory simulation program DAMP (Reference 13). The density, specific heat, thermal conductivity, and viscosity equations are

$$\rho = 93.1048 - .079178 (T-492) \quad [lbm/ft^3],$$

$$C_p = -6.326 + 4.244 \times 10^{-2} T - 8.939 \times 10^{-5} T^2 \\ + 6.253 \times 10^{-8} T^3 \quad [B/lbm-^{\circ}R],$$

$$K = .036 (-2.804 + 2.286 \times 10^{-2} T - 2.554 \times 10^{-5} T^2) \quad [B/ft-hr-^{\circ}R],$$

$$\text{and } \mu = 10^{-4} (10.715 - .0149 T) \quad [lbm/ft-sec].$$

### Aerozine 50 (A-50)

The fluid properties of A-50 in the liquid state are evaluated from the following functions which also were obtained from Reference 13

$$\rho = 57.6095 - .032518 (T-492) \quad [lbm/ft^3],$$

$$C_p = .55148 + 2.67 \times 10^{-4} T \quad [B/lbm-^{\circ}R],$$

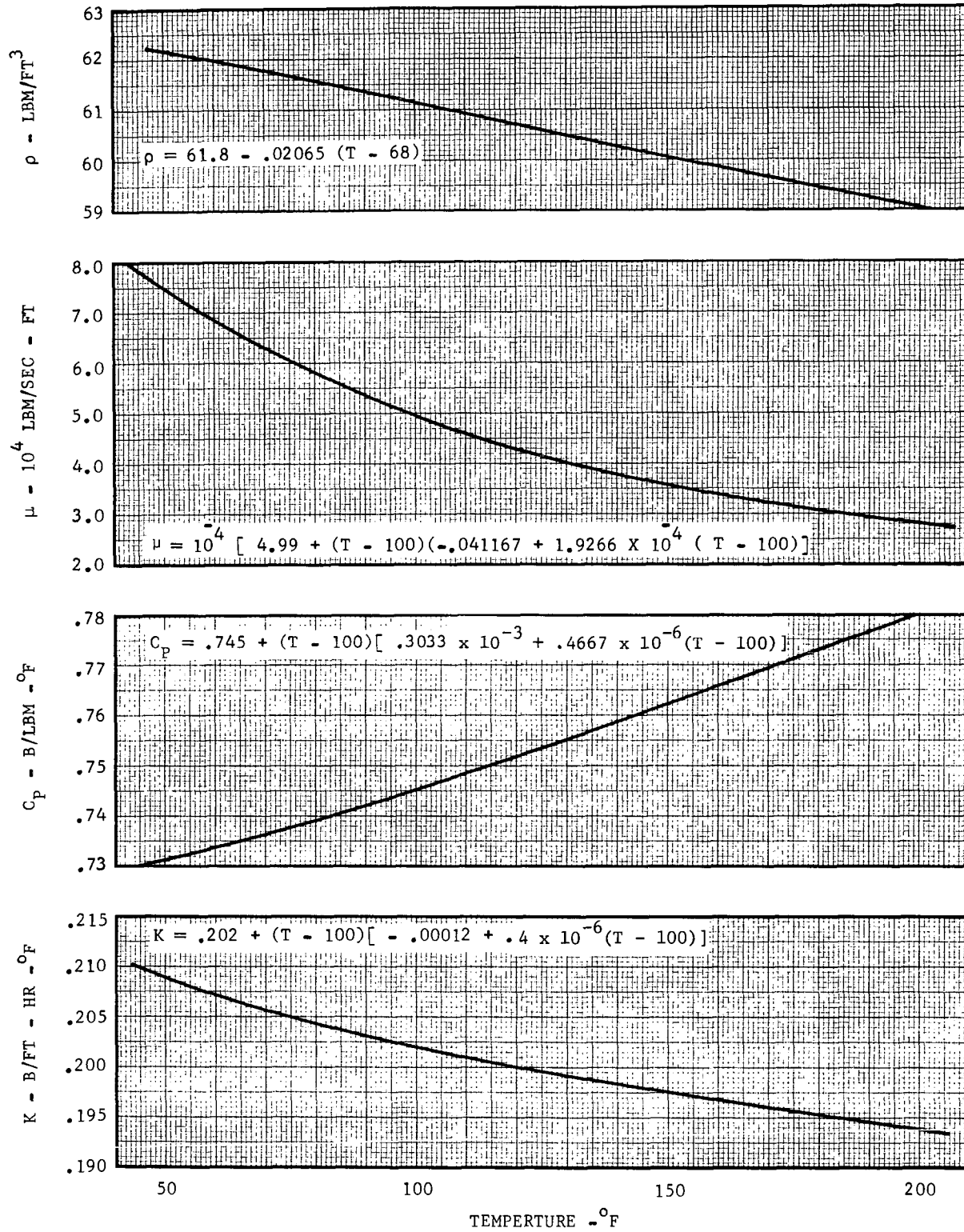
$$K = .36 (.5393 - 7.7436 \times 10^{-4} T + 8.5161 \times 10^{-7} T^2) \quad [B/ft-hr-^{\circ}R],$$

$$\text{and } \mu = 10^{-4} (492.619 - 2.36466 T + 3.831 \times 10^{-3} T^2 \\ - 2.08 \times 10^{-6} T^3) \quad [lbm/ft-sec].$$

### Hydrazine ( $N_2H_4$ )

The fluid properties of liquid hydrazine in the range of about 50 to 200°F are evaluated according to equations obtained by curve-fitting data supplied in Reference 14. These equations and the corresponding curves are shown in **Figure 5.3**.

Figure 5.3 Hydrazine Fluid Properties



### Two-Phase Fluid Properties

For the operation of the steady-state heat exchanger model with boiling fluid, properties are required at saturated liquid and saturated vapor conditions. Subroutines to compute the following two-phase boundary properties are supplied for both hydrogen and oxygen fluids.

Linear interpolation is used within special data tables to compute the saturation temperature and the enthalpies, densities, and, for oxygen, the specific heat at the saturated liquid and saturated gas conditions. The thermal conductivity, viscosity, and specific heat of hydrogen are obtained by calls to the general cryogenic property routines. The fluid pressure and the corresponding saturation temperature plus or minus 0.5 degree are the independent variables used to produce values at saturated vapor and saturated liquid condition, respectively.

## 6.0 COMBUSTION CHARACTERIZATION

The combustion chamber module was designed to employ data which characterizes the combustion of various propellant combinations. Data for the combinations  $H_2/O_2$ ,  $N_2O_4/A-50$ , and hydrazine monopropellant have been incorporated. The fluid properties employed are the theoretical characteristic exhaust velocity ( $C^*$ ), combustion temperature ( $T_c$ ), specific heat ratio ( $\gamma$ ), and specific heat ( $C_p$ ). These data are supplied in tabular form in terms of two independent variables, pressure (P) and mixture ratio (MR). Two-dimensional linear interpolation is used.

### Hydrogen/Oxygen

The characterization data for the combustion of hydrogen and oxygen were obtained from a series of executions of the ICRPG ODE rocket engine program in which the mixture ratio was varied over the range  $0.5 < MR < 6.0$  and the chamber pressure was independently varied over the range  $100 < P < 500$  psi. The results are shown plotted in Figures 6.1 through 6.4.

### $N_2O_4/A-50$

The characterization data for the combustion of  $N_2O_4$  and A-50 were obtained from Reference 15. Figures 6.5 through 6.8 show these data in the range  $.25 < MR < 4.0$  for chamber pressures of 150 and 450 psi.

### Hydrazine Monopropellant

The catalytic decomposition of hydrazine is characterized by the single independent variable - fraction of  $NH_3$  dissociated. Figures 6.9 through 6.12 show the four characterization curves. These data were obtained from Reference 16.

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Figure 6.1  $H_2/O_2$  Characteristic Exhaust Velocity,  $C^*$

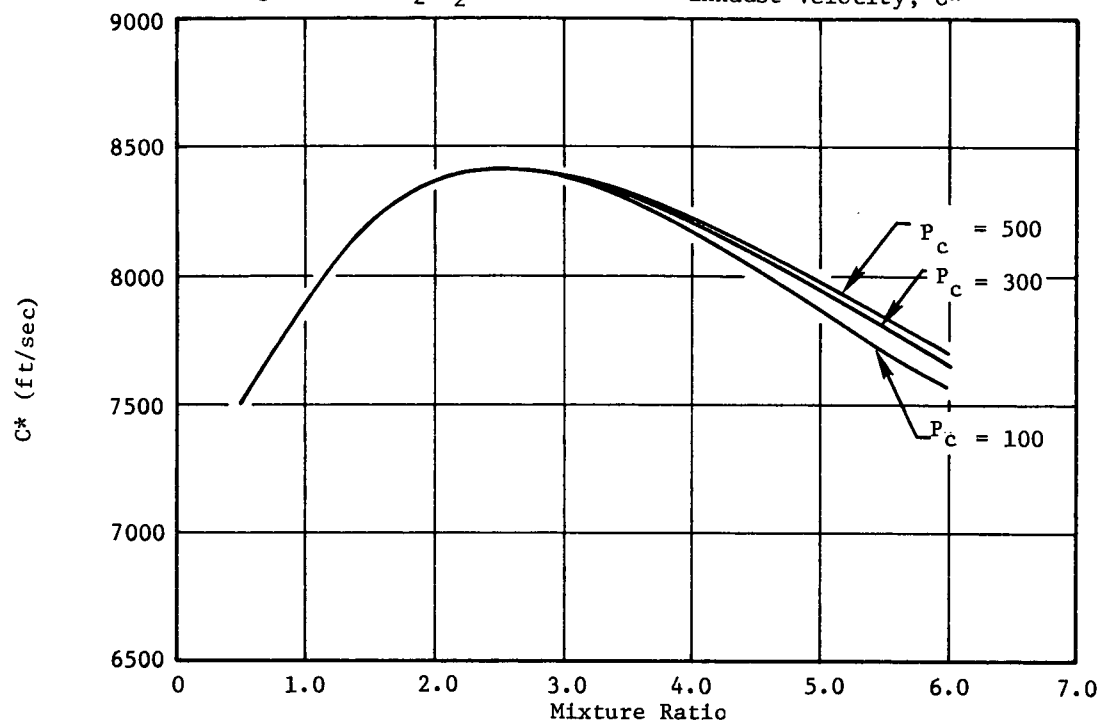


Figure 6.2  $H_2/O_2$  Combustion Temperature,  $T_c$

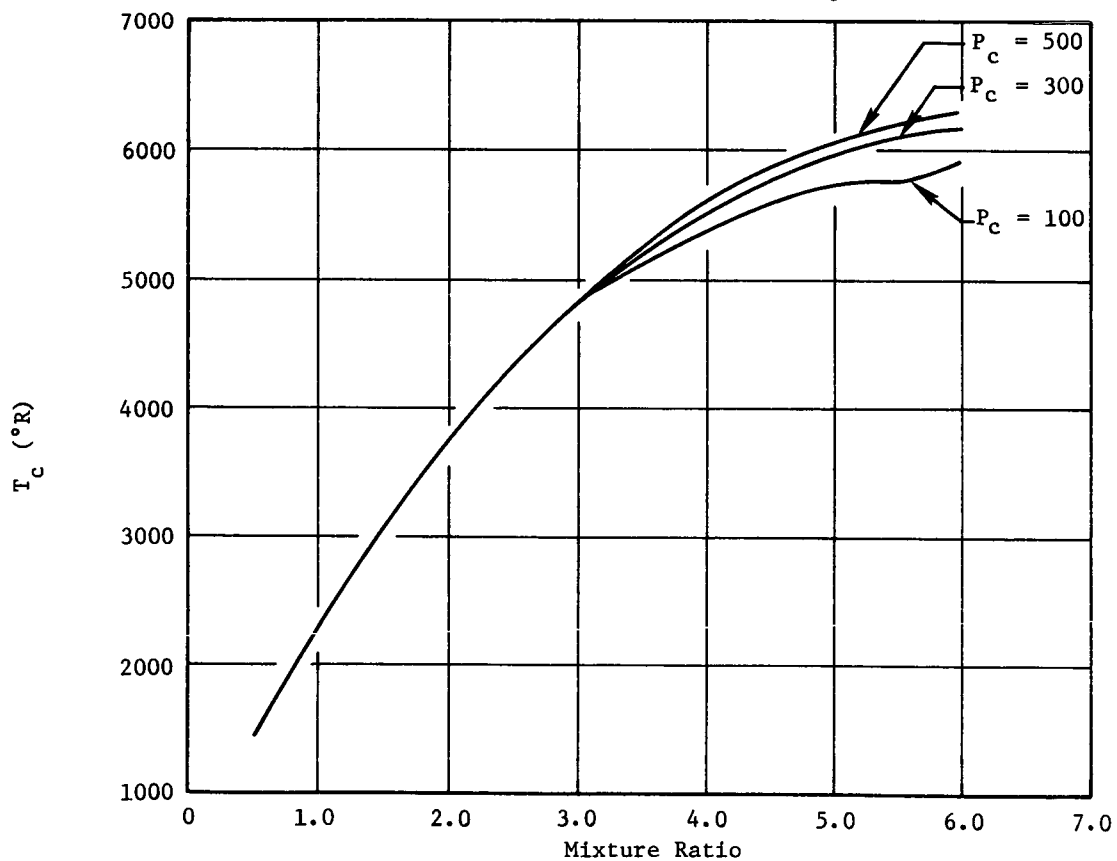


Figure 6.3.  $H_2/O_2$  Specific Heat Ratio,  $\gamma$

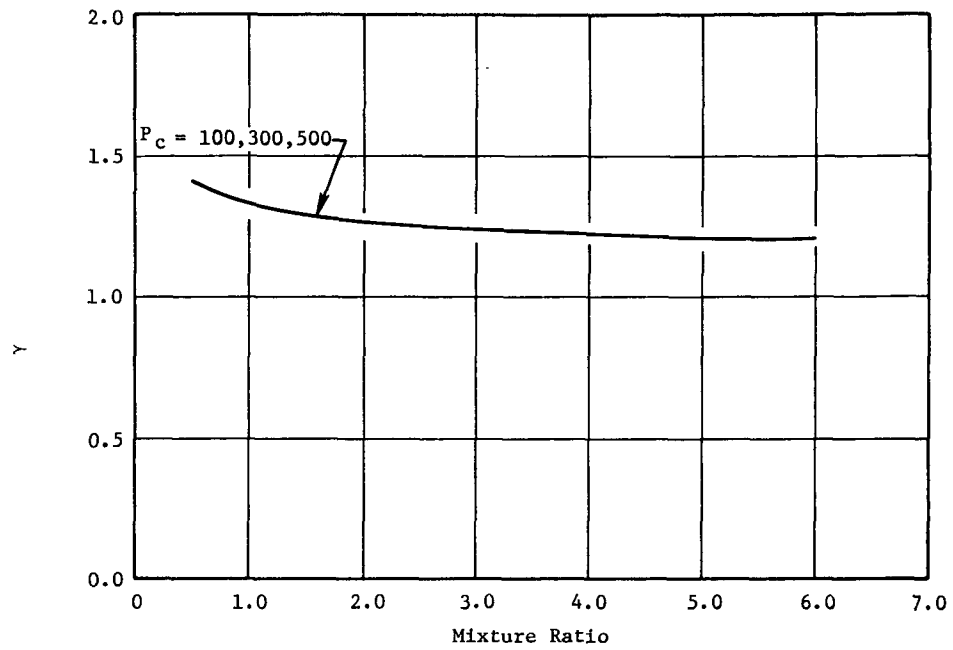


Figure 6.4.  $H_2/O_2$  Specific Heat,  $C_p$

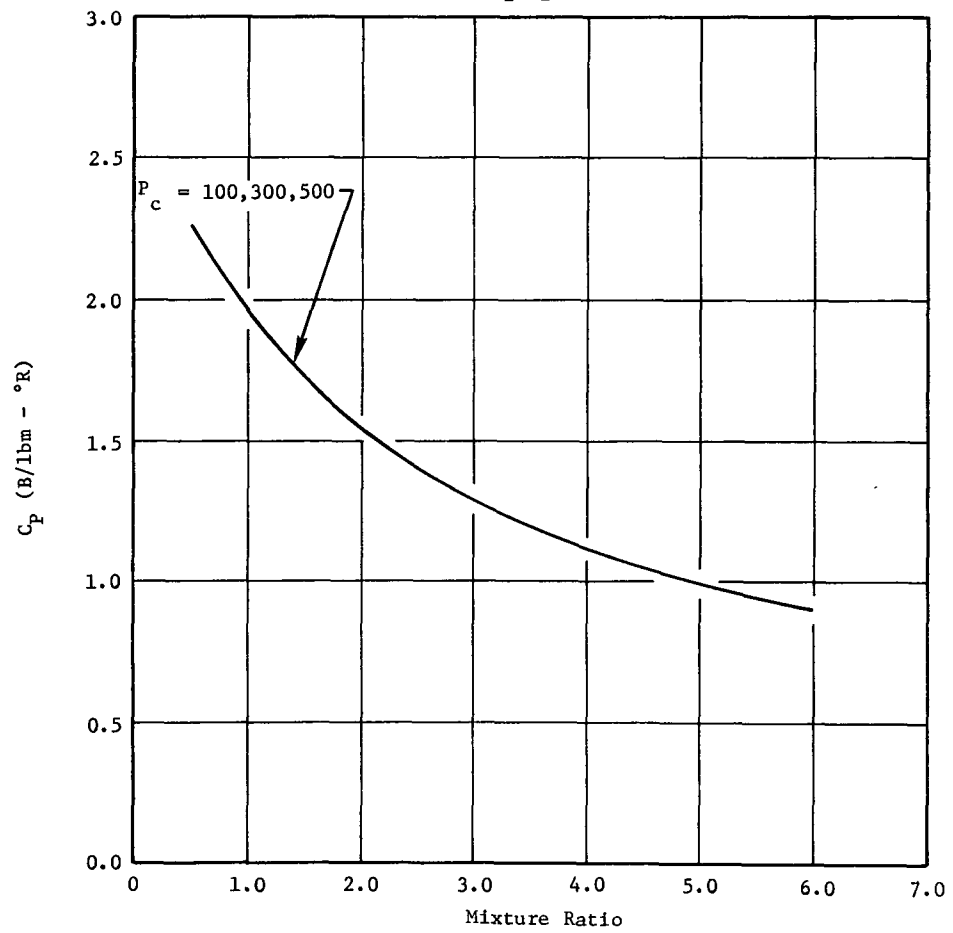


Figure 6.5 A-50/N<sub>2</sub>O<sub>4</sub> Characteristic Exhaust Velocity, C\*

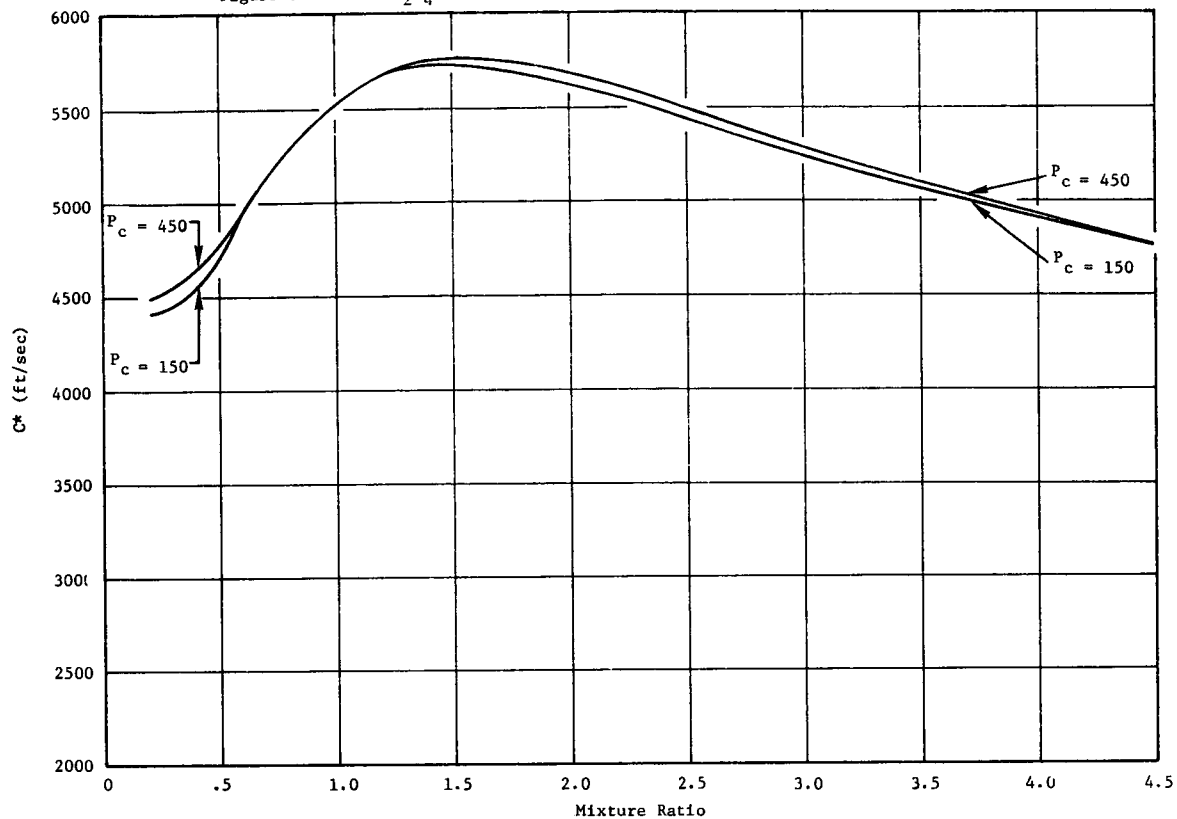


Figure 6.6 A-50/N<sub>2</sub>O<sub>4</sub> Combustion Temperature  $T_c$

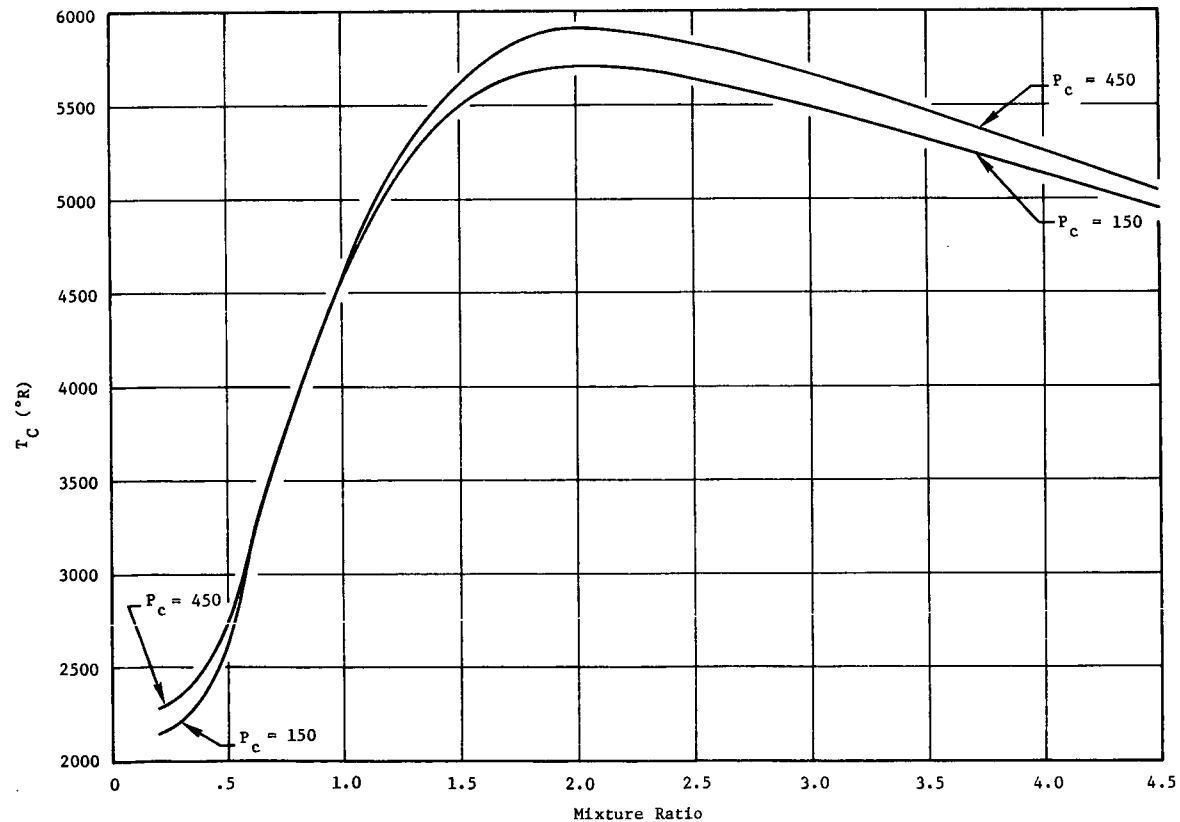


Figure 6.7 A-50/N<sub>2</sub>O<sub>4</sub> Specific Heat Ratio,  $\gamma$

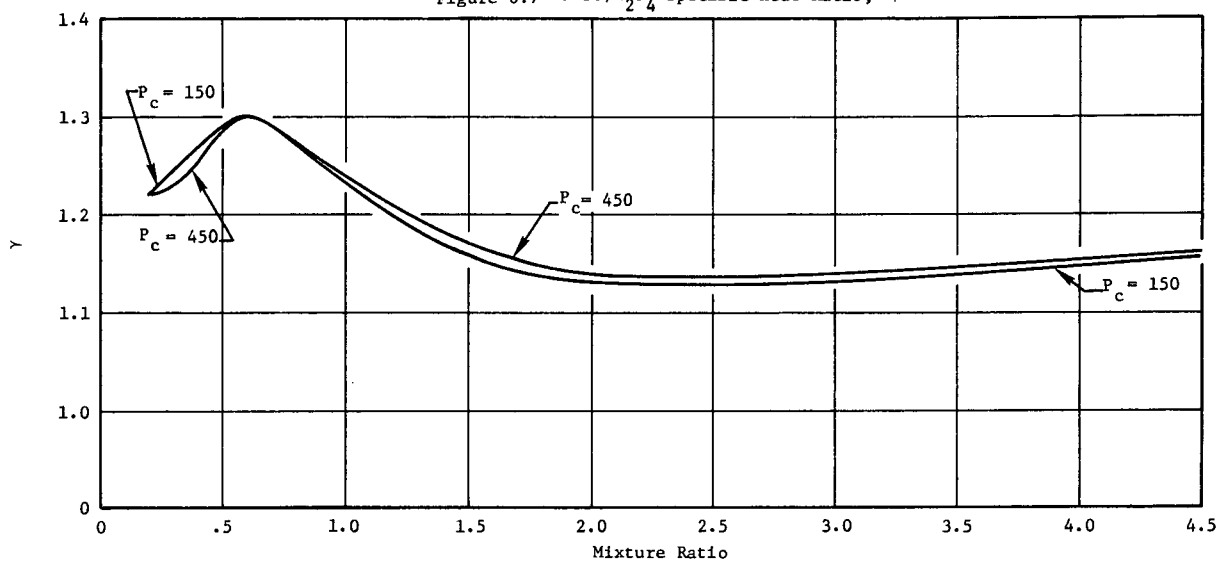


Figure 6.8 A-50/N<sub>2</sub>O<sub>4</sub> Specific Heat,  $C_p$

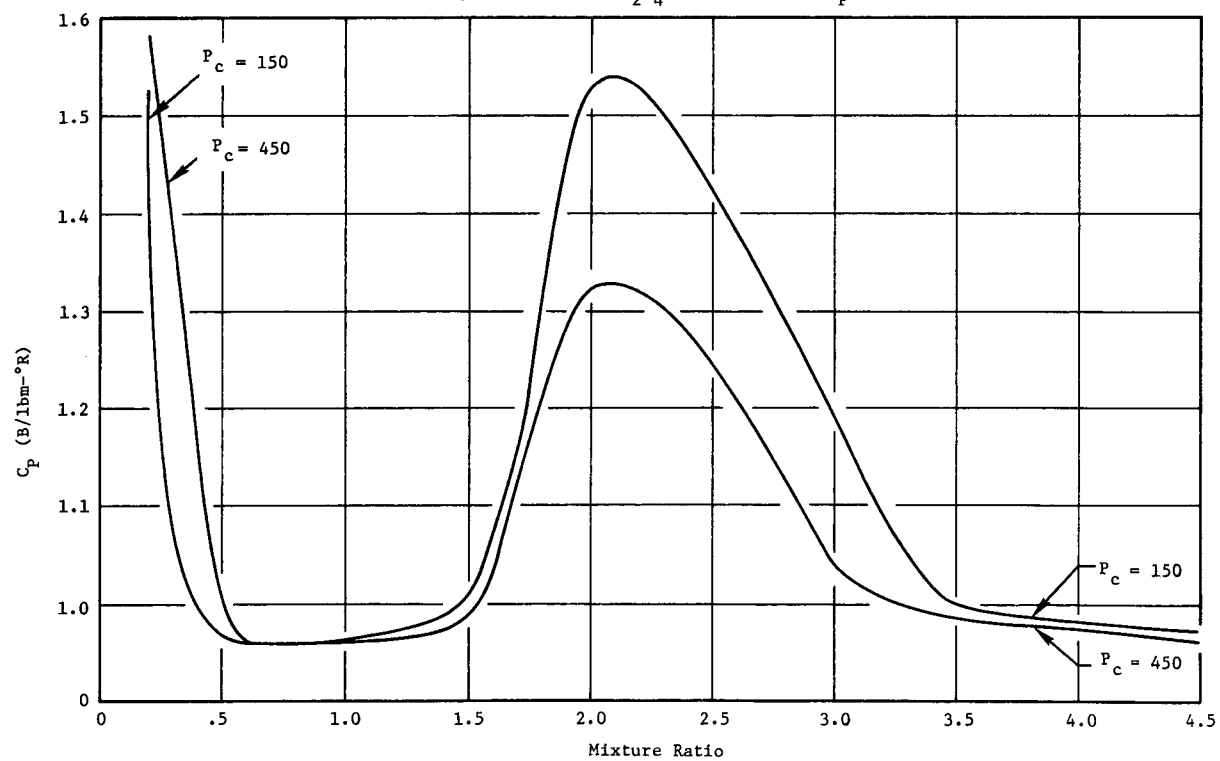


Figure 6.9 Hydrazine Monopropellant Characteristic Exhaust Velocity  $C^*$

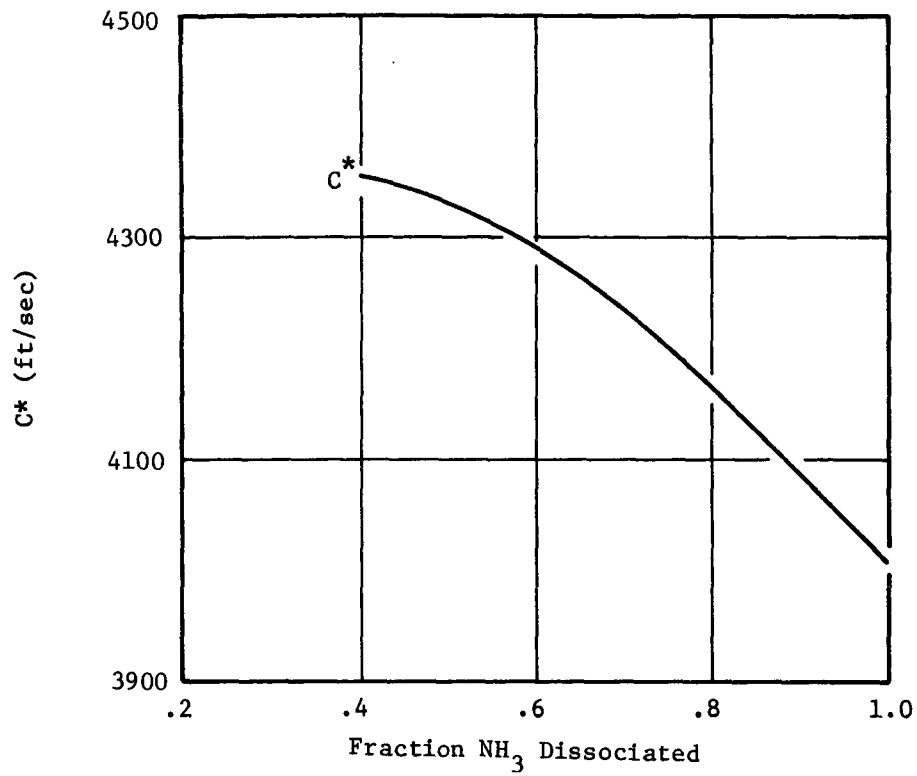


Figure 6.10 Hydrazine Monopropellant Combustion Temperature,  $T_C$

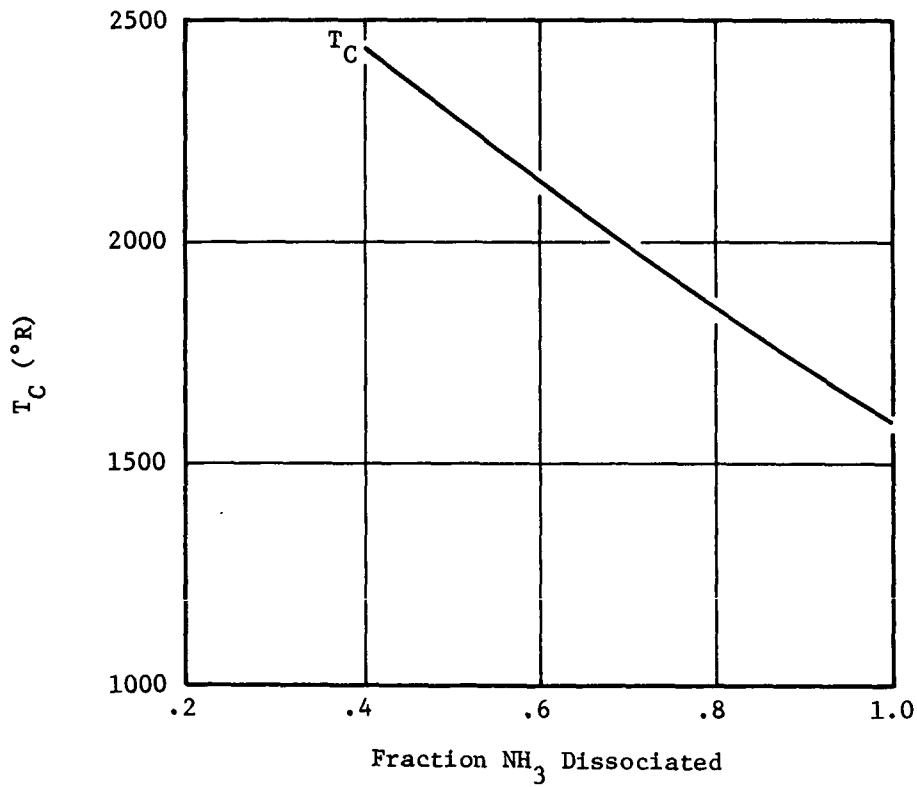


Figure 6.11 Hydrazine Monopropellant Specific Heat Ratio,  $\gamma$

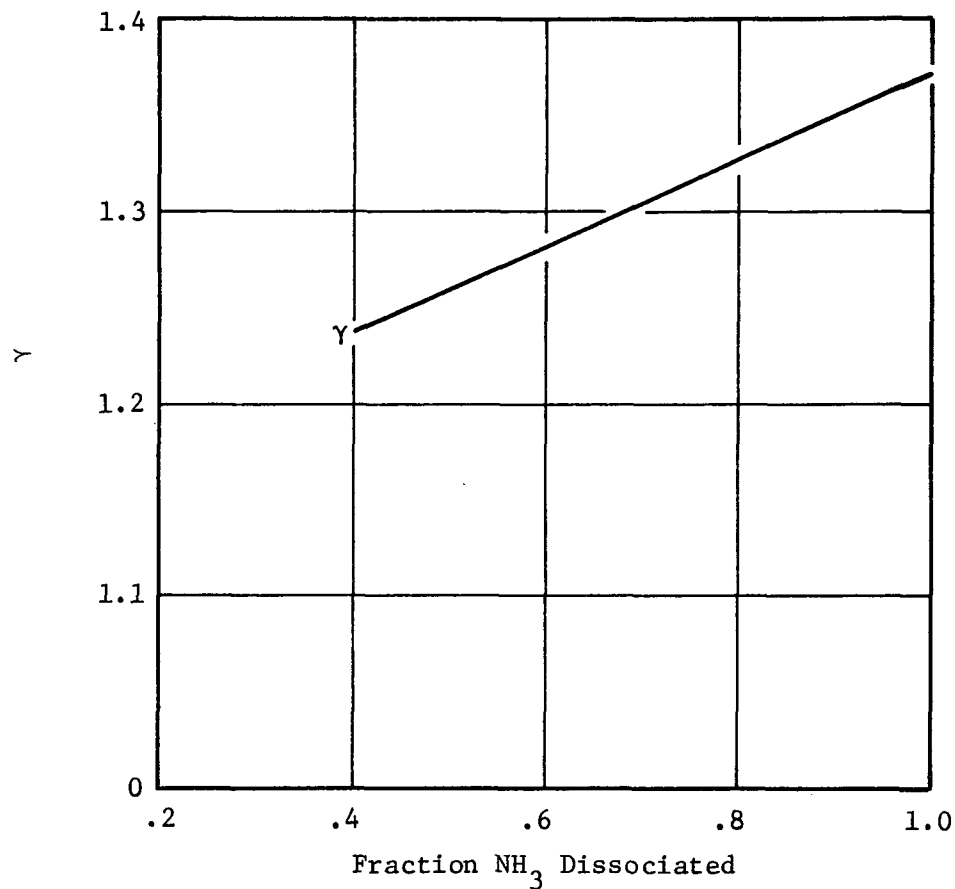
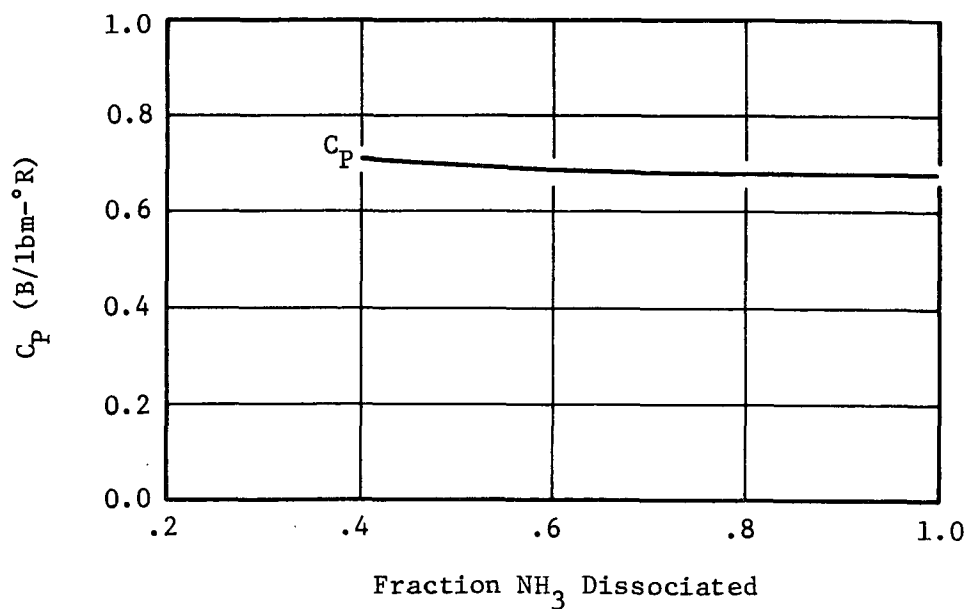


Figure 6.12 Hydrazine Monopropellant Specific Heat,  $C_P$



## 7.0 SAMPLE CASE ONE - DESIGN OF AN ACPS

This test case was designed to verify the integrated operation of several component modules and to demonstrate a variety of program features applied to a realistic ACPS design problem.

The objective of this problem was to size a thrust chamber and feed system to produce a specified thrust at a specified design chamber pressure and mixture ratio. The feed system consisted of propellant storage tanks, a regulator, lines, valves, and dual turbopumps driven by a common hydrazine monopropellant gas generator. The main propellants were Aerozine-50 and Nitrogen Tetroxide. The system configuration is shown in Figure 7.1.

Restrictions imposed on the system design were as follows. The combustion chamber had an expansion ratio of 40 and operated with known combustion and nozzle efficiencies. The throat area and the two injector flow areas were to be sized to produce a vacuum thrust of 3500 lbf operating with a chamber pressure of 350 psi and a mixture ratio of 1.5.

Feed lines numbered 10 and 14 (Figure 7.1) were 50 ft long and were to be sized to produce a 10 psi pressure drop. The remainder of the lines were short and were considered frictionless and adiabatic. Shut-off valves V3 and V4 were to be sized to produce a 10 psi pressure drop. Valves V1 and V2 were fixed, having flow areas of  $1 \text{ in}^2$ .

The two pumps were considered off-the-shelf components having known characteristics operating at a design speed of 50,000 RPM. These pumps were driven by separate gas turbines having known characteristics. By adjusting the effective areas of the inlet sonic nozzles, the turbines were to be sized to produce the required power. The exit areas of the turbine exhaust ducts were to be sized to be consistent with a 10 psi back pressure.

The main propellants in the system were supplied from storage tanks at a pressure of 20 psi. The hydrazine monopropellant was delivered from a storage tank at 300 psi and was regulated to 200 psi before entering the gas generator which operates at 80 percent  $\text{NH}_3$  dissociation.

The various prescribed configuration data are shown in Figure 7.1. Also shown are the seven optional design constraints that were placed upon the performance of the system. From physical considerations, an additional nine constraining relationships, required to insure internal consistency, were imposed automatically by the program. The total number of constraints

on the system performance, therefore, was 16. These constraints were to be satisfied by finding a particular set of values of the 11 unspecified component dimensions and 5 unknown system flowrates. These 16 state variables are listed in Figure 7.1 and are shown encircled next to the corresponding components.

The resulting set of 16 non-linear equations in 16 unknowns provides a determinate system which was evaluated iteratively by the program equation solver. The solution to the entire design problem required 18 iterations and six seconds of computer time. The initial estimates of the state variables were 5% to 33% in error. The rms error of the constraining functions was reduced from .16 to  $.64 \times 10^{-6}$ , and the state variable solution values were determined to an accuracy of better than .003%.

Figure 7.2 shows the solution values obtained from the computer run along with other significant data indicating the balanced system operating conditions. All design requirements were accurately satisfied.

The computer printout included at the end of this section presents the following information.

- (1) The input data used to execute this system design case. The data are grouped according to the headings
  - (a) SYSCOM - System definition providing the proper component execution sequence.
  - (b) STATE - List of state variables.
  - (c) COMPONENT CONNECTIONS - Identification numbers of lines connecting the various components.
  - (d) COMPONENT SPECIFICATIONS - Description and performance characterization of individual components.
  - (e) DESIGN CONSTRAINTS - Specification of performance constraints to be achieved by system sizing.
  - (f) ESTIMATE OF STATE VARIABLES - Estimated values of state variables to be used as starting points.
  - (g) EQUATION SOLVER - Data controlling operation and convergence of program equation solver.
- (2) The Matrix of partial derivatives  $df_j/dX_i$  evaluated at the conditions of the initial state vector. Each column corresponds to a state variable and each row to a constraint equation. The elements in the matrix show the relative sensitivity of the constraints to variations in the state variables.



- (3) Summary of the convergence process showing
- (a) Number of iterations required (18).
  - (b) The norm of the constraint vector.
  - (c) Solution state variable values (X).
  - (d) Normalized state variable values (Y) (relative to the initial estimates).
  - (e) Values of Y at which the associated columns of the partial matrix were updated (YM).
  - (f) Normalizing values  $Y_i = X_i / X_{refi}$ .
  - (g) Last corrections made to  $Y_i$ .
  - (h) Last values of constraint functions,  $f_j (Z)$ .
  - (i) 1108 execution time required to obtain solution.
- (4) Operating conditions of each component module executed in the system. At the end is the summary of the constraint values.

It is recognized that working with performance curves and a desk calculator, some of the results (sizing of the combustion chamber throat area, valve areas, and line diameters) could have been obtained manually. However, the balanced feed system results could not realistically have been so obtained.

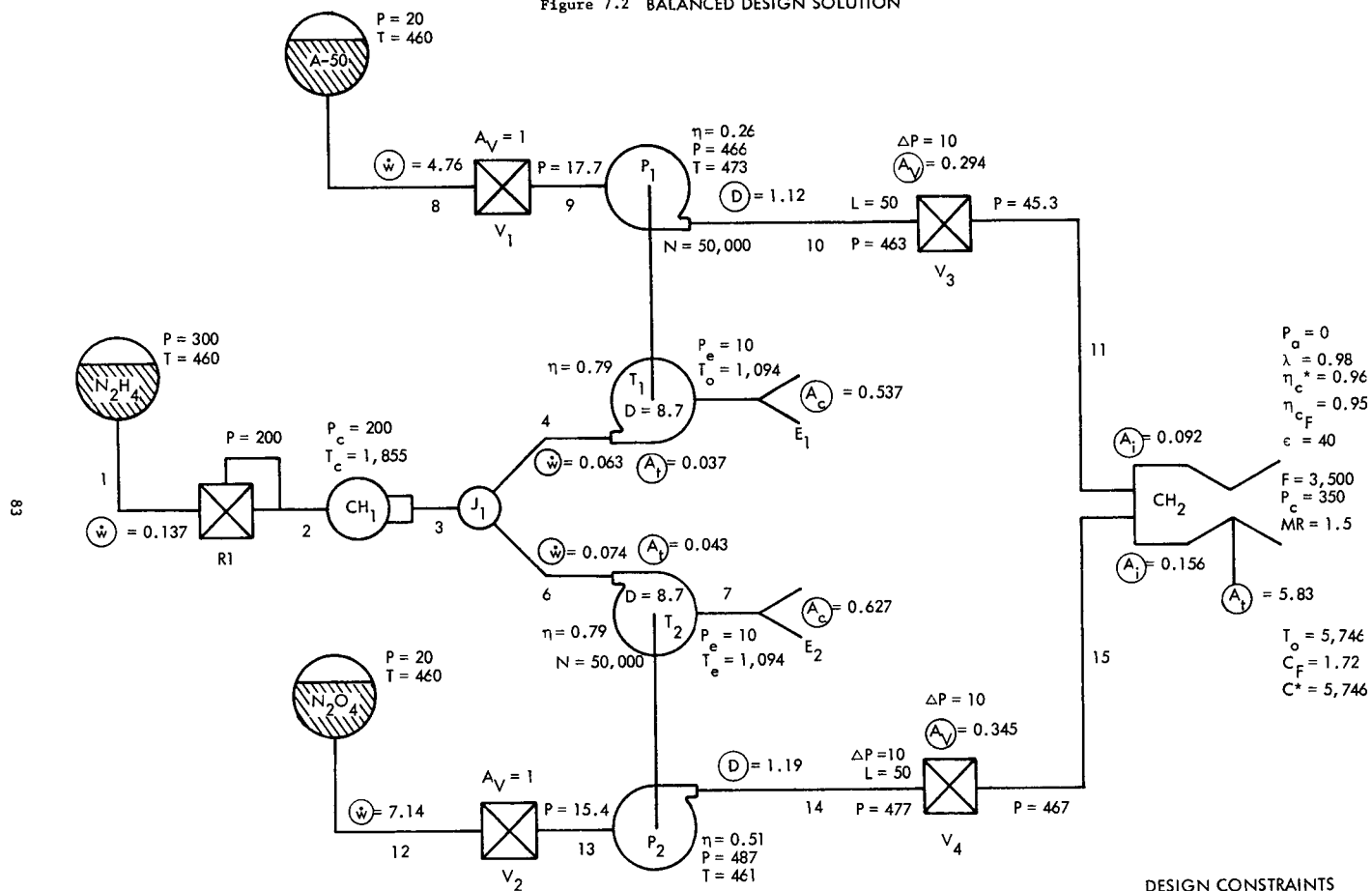
This demonstration case forms the basis of a representative study of the response of the configured system to variations in the regulator setting. The results of this study are presented in Section 8.0.

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1.  $\Delta P_{v3} = 10$
2.  $\Delta P_{v4} = 10$
3.  $\Delta P_{L10} = 10$
4.  $\Delta P_{L14} = 10$
5.  $F = 3,500$
6.  $P_c = 350$
7.  $MR = 1.5$

Figure 7.2 BALANCED DESIGN SOLUTION



STATE VARIABLES

- |                    |                        |                         |
|--------------------|------------------------|-------------------------|
| 1. $W_1 = 0.137$   | 6. $A_{tur 1} = 0.037$ | 11. $A_{inj 1} = 0.092$ |
| 2. $W_4 = 0.063$   | 7. $A_{tur 2} = 0.043$ | 12. $A_{inj 2} = 0.156$ |
| 3. $W_6 = 0.074$   | 8. $A_c 1 = 0.537$     | 13. $A_v 3 = 0.294$     |
| 4. $W_8 = 4.76$    | 9. $A_c 2 = 0.627$     | 14. $A_v 4 = 0.345$     |
| 5. $W_{12} = 7.14$ | 10. $A_t = 5.83$       | 15. $D_{10} = 1.12$     |
|                    |                        | 16. $D_{14} = 1.19$     |

DESIGN CONSTRAINTS

1.  $\Delta P_{v3} = 10$
2.  $\Delta P_{v4} = 10$
3.  $\Delta P_{L10} = 10$
4.  $\Delta P_{L14} = 10$
5.  $F = 3,500$
6.  $P_c = 350$
7.  $MR = 1.5$

# SAMPLE CASE ONE -- INPUT DATA

```

• ACPS PROGRAM PROOF CASE 7/14/72
• MODIFICATION DATE : 8/03/72
•
• A-50 / N204 HIGH PC THRUSTOR
• DUAL TURBOPUMPS DRIVEN BY HYDROZINE MONO GG
• CHAMBER CONSTRAINTS - PC, F, MR
•
• DESIGN MODE
•
SYSCOM = TANK,1, LINE,1, PREG,1, LINE,2, CHAM,1, LINE,3, JUNCT,1,
        LINE,4, TURB,1, LINE,5, CHOKE,1,
        LINE,6, TURB,2, LINE,7, CHOKE,2,
        TANK,2, LINE,8, VALVL,1, LINE,9, PUMP,1, LINE,10, VALVL,3, LINE,11,
        TANK,3, LINE,12, VALVL,2, LINE,13, PUMP,2, LINE,14, VALVL,4, LINE,15,
        CHAM,2
•
STATE = WDOT,1, WDOT,4, WDOT,6, AEFTUR,1, AEFTUR,2,
        ACHOK,1, ACHOK,2, WDOT,8, WDOT,12, AREAT,2,
        ARINJ1,2, ARINJ2,2, CDAV,3, CDAV,4, DIALI,10, DIALI,14
•
• COMPONENT CONNECTIONS
LOWO = 1,8,12
LVAI = 8,12,10,14
LVAO = 9,13,11,15
LPRI = 1
LPRO = 2
LCHA1 = 2,11
LCHA2(2) = 15
LCHAM = 3
LIJU1 = 3
LOJU1 = 4,6
LTURB1 = 4,6
LTURB2 = 5,7
LCHOKE = 5,7
LPUMP1 = 9,13
LPUMP2 = 10,14
•
• TANKS
• VALVES
• REGULATOR
• CHAMBERS
• JUNCTIONS
• TURBINES
• EXITS
• PUMPS
•
• COMPONENT SPECIFICATIONS
•
• TANKS
VTANK = 20.,2000.,2000.
PTANK = 300.,20.,20.
TTANK = 3R460.
WOL = 400.,4.E4,4.E4
TLIQ = 3R460.
CPI = 3R3.45
RI = 3R772.83
•

```

```

* LINES
LTYPE = 15R4
LTYPE(10) = 1
LTYPE(14) = 1
DIAL1 = 15R1.
DIAL1(3) = 5R3.
XLENG1(10) = 50.
XLENG1(14) = 50.
NPLINE = 2R-6,5R10,4R-3,4R-4
*
* TURBINES
CEF1 = 2R5.2
CEF2 = 2R-8.6
RPM1 = 5.E4
DIAT = 8.7, 8.7
RPMT = 2R 5.E4
PTURBO = 10., 10.
* PUMP
ITURB = 1,2
GR = 1.
RPM1 = 2R5.E4
RDPUMP(1) = 1.
RDPUMP(2) = 1.
POW1 = 2R.147E5, POW1 = 2R.110E4, POW2 = 2R.250E2, POW3 = 2R.391
POW1 = 2R.417E3, PW1 = 2R.801E1, PW2 = 2R-.169E1 * PUMP CURVES
*
* VALVES
CDAV = 1., 1.
PRE(1) = 200.
*
* COMBUSTION CHAMBERS
PATM = 0.
DISOC(1) = 0.8 * MONO GG DISSOC
ARINJ1(1) = .4
ERATIO(2) = 40.
LAMDA (2) = .9806 * 16 DEG DIV. LOSS
ECSTAR(2) = .96 * C-STAR EFFICIENCY
ECSTAR(1) = .93 * C-STAR EFFICIENCY - GG
ECF (2) = .95 * CF EFFICIENCY
*
* DESIGN CONSTRAINTS
*
CHAMMR(2) = 1.5
PCD(2) = 350.
THRTO(2) = 3500.
DPVALV(3) = 10.
DPVALV(4) = 10.
DPLINE(10) = 10.
DPLINE(14) = 10.
*

```

• ESTIMATE OF STATE VARIABLES

•

WDOT(1) = .2

WDOT(4) = .1

WDOT(6) = .11

AEFTUR(1) = .1

AEFTUR(2) = .1

ACHOKE(1) = 1.

ACHOKE(2) = 1.

WDOT(8) = 5.

WDOT(12) = 7.

AREAT (2) = 8.

ARINJ1(2) = .1

ARINJ2(2) = .2

CDAV(3) = .2

CDAV(4) = .4

DIALI(10) = .8

DIALI(14) = .8

•

• EQUATION SOLVER

•

MAXIT = 30

DYLIM = .2

DYUP = .2

YBNDL = 0.

EPSDY = 1.E-6

EPSZ = 1.E-6

•

•

•

•

ENDCAS

SAMPLE CASE ONE -

PARTIAL DERIVATIVE MATRIX

1	-.48780	.24390	.26829	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
2	-.00008	-.57956	.00000	.56819	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
3	-.00003	-.84152	.00000	.00000	.00000	.83199	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
4	-.00008	.00000	-.63751	.00000	.62501	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
5	-.00003	.00000	-.92326	.00000	.00000	.00000	.91440	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
6	-.00004	-1.55753	.00000	.00000	.00000	.00000	.00000	.51236	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
7	.00000	.00000	.00000	.00000	.00000	.00000	.00000	-9.79994	.00000	.00000	.00000	.00000	.00000	.00000	24.55442	.00000
8	.00000	.00000	.00000	.00000	.00000	.00000	.00000	-4.82525	.00000	.00000	.00000	.00000	.00000	4.64506	.00000	.00000
9	-.00004	.00000	-1.50523	.00000	.00000	.00000	.00000	.00000	.66467	.00000	.00000	.00000	.00000	.00000	.00000	.00000
10	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	-12.81368	.00000	.00000	.00000	.00000	.00000	.00000	30.92106
11	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	-1.44800	.00000	.00000	.00000	.00000	.00000	1.39256	.00000
12	.00000	.00000	.00000	.00000	.00000	.00000	.00000	-1.18317	.80601	.00000	.69729	-.43801	.17167	-.04570	.89033	-.99865
13	-.00000	.00000	.00000	.00000	-.00000	-.00000	-.00000	-.64104	-.78888	.78376	.22920	.16253	.05689	.01702	.29803	.36897
14	-.00000	.00000	.00000	.00000	.00000	.00000	.00000	-.23407	-.44204	.71902	-.00071	-.00051	-.00018	-.00005	-.00094	-.00119
15	-.00000	.00000	.00000	.00000	.00000	.00000	.00000	-.08020	-.67303	.00656	.00085	.00060	.00020	.00006	.00111	.00140
16	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.91503	-.93333	.00000	.00000	.00000	.00000	.00000	.00000	.00000

# SAMPLE CASE ONE - CONVERGENCE SUMMARY

NON-LINEAR SOLUTION IT = 18 FNORM = .66767-06

I	X	Y	Y PARTIAL	X REF	UY	Z
1	.136888+00	.68444	.68803	.2000+00	-.3423-07	.0000
2	.631790-01	.63179	.63314	.1000+00	-.3062-07	-.1490-07
3	.737088-01	.67008	.67539	.1100+00	-.3422-07	.1490-07
4	.366146-01	.36615	.31404	.1000+00	-.2127-06	.0000
5	.427170-01	.42717	.60000	.1000+00	.5057-06	.0000
6	.537460+00	.53746	.60000	.1000+01	-.7639-07	.0000
7	.626668+00	.62667	.60237	.1000+01	-.3139-07	-.1067-04
8	.475690+01	.95138	1.00000	.5000+01	-.6585-07	.0000
9	.713536+01	1.01934	1.00000	.7000+01	-.3702-07	.0000
10	.582542+01	.72818	.67619	.8000+01	-.3102-06	.3874-06
11	.919471-01	.91947	1.00000	.1000+00	-.1444-06	.0000
12	.157058+00	.78529	.75135	.2000+00	.6118-06	-.3129-06
13	.294333+00	1.47167	1.43455	.2000+00	-.4215-06	-.1937-06
14	.345305+00	.86326	1.00000	.4000+00	-.3849-07	-.2980-07
15	.112024+01	1.40030	1.22322	.8000+00	-.2899-05	-.1490-07
16	.118846+01	1.46558	1.45836	.8000+00	-.4199-06	.0000

SOLUTION ELAPSED TIME = .126 MINUTES



SAMPLE CASE ONE - COMPUTER SOLUTION

STATE VARIABLES

WDOT ( 1 ) = 1.368879-01	WDOT ( 4 ) = 6.317903-02	WDOT ( 6 ) = 7.370882-02	AFTUR( 1 ) = 3.661457-02
AFTUR( 2 ) = 4.271697-02	ACHOKE( 1 ) = 5.374601-01	ACHOKE( 2 ) = 6.266684-01	WDOT ( 8 ) = 4.756904+00
WDOT (12) = 7.135355+00	AREAT ( 2 ) = 5.825422+00	ARINJ1( 2 ) = 9.194705-02	ARINJ2( 2 ) = 1.570575-01
CDAV ( 3 ) = 2.943331-01	CDAV ( 4 ) = 3.453055-01	DIALI (10) = 1.120237+00	DIALI (14) = 1.188464+00

• • TANK NO. 1 • • LGI 0 LGO 0 LWI 0 LWO 1

TIME 0.00000	P TANK 2.99999+02	T GAS 4.60000+02	T LIQ 4.60000+02	W LIQ 4.00000+02
M 1 1.52529+00	M 2 0.00000	ALPHA 0.00000	ENERGY 1.72380+03	RHO L 5.37052+01
DM1 0.00000	DM2 0.00000	OW NET -1.36888-01	DU -1.41503-01	DWIN 0.00000
CP1 3.45000+00	CP2 0.00000	RGAS 1 7.72830+02	RGAS 2 0.00000	V TANK 2.00000+01
DMVENT 0.00000	PVENT 0.00000	AVENT 0.00000	1-PG/P	1-PL/P

• • • FRICTIONLESS - ADIABATIC LINE 1 FLUID 6

W DOT 1.36888-01	PRES 2.99998+02	TEMP 4.60000+02	PRES T 2.99999+02	TEMP T 4.60000+02
------------------	-----------------	-----------------	-------------------	-------------------

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• • • • REGULATOR NO. 1 • • LINE NO. INLET 1 OUTLET 2

PA 2.99998+02	TA 4.60000+02	FUNC 0.00000	FUNCP 0.00000	RHO2 5.37052+01
PB 2.00000+02	TB 4.60000+02	WDOT 1.36888-01	IPROP 6	
ENTHA 0.00000	ENTHB 0.00000			

• • • FRICTIONLESS - ADIABATIC LINE 2 FLUID 6

W DOT 1.36888-01	PRES 2.00000+02	TEMP 4.60000+02	PRES T 2.00002+02	TEMP T 4.60000+02
------------------	-----------------	-----------------	-------------------	-------------------

• • COMBUSTION CHAMBER NO. 1 • •

LINE 1 2 FLUID 6	PC FLO 1.99995+02	T LINE 4.60000+02	W DOT 1.36888-01	CD*A 4.00000-01
LINE 2 0 FLUID 4	PC FLO 3.50000+02	T LINE 0.00000	W DOT 7.13536+00	CD*A 1.57058-01
MR 8.00000-01	P CHAM 1.99995+02	T CHAM 1.85500+03	W NOZ 1.36888-01	THRT 0.00000
ISP 2.94309+02	CSTAR 1.67000+03	C F 1.71661+00	GAMMA 1.32700+00	CP 5.48887-01

• • • FRICTIONLESS - ADIABATIC LINE 3 FLUID 10

W DOT 1.36888-01	PRES 1.99989+02	TEMP 1.85499+03	PRES T 1.99995+02	TEMP T 1.85500+03
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• • • • JUNCTION NO. 1

LINE 3 IN	W DOT 1.36888-01	PRES T 1.99995+02	TEMP T 1.85500+03	PRES 1.99989+02
LINE 4 OUT	W DOT 6.31790-02	PRES T 1.99995+02	TEMP T 1.85500+03	PRES
LINE 6 OUT	W DOT 7.37088-02	PRES T 1.99995+02	TEMP T 1.85500+03	PRES

• • • FRICTIONLESS - ADIABATIC LINE 4 FLUID 10

W DOT 6.31790-02	PRES 1.99994+02	TEMP 1.85500+03	PRES T 1.99995+02	TEMP T 1.85500+03
------------------	-----------------	-----------------	-------------------	-------------------

\* \* TURBINE 1 LINE IN = 4 LINE OUT = 5

PT IN	1.99995+02	TT IN	1.85500+03	WDOT 1	6.31790-02	CP TUR	5.48867-01	GAMMA	1.32700+00
PT OUT	1.00000+01	TT OUT	1.09382+03	W TURB	6.31790-02	AETUR	3.66146-02	DIAT	8.70000+00
PWNT	2.05404+04	ETA T	7.86047-01	CEFI	5.20000+00	CEFC	-8.60000+00	U/C	3.02326-01

\* \* \* FRICTIONLESS - ADIABATIC LINE 5 FLUID 10  
W DOT 6.31790-02 PRES 1.00000+01

TEMP 1.09382+03 PRES T 1.00181+01 TEMP T 1.09421+03

\* \* CHOKED EXIT 1 LINE 5

WCHOKE	6.31790-02	PRES T	1.00181+01	TEMP T	1.09421+03	GAMMA	1.32700+00	ACHOKE	5.37460-01
--------	------------	--------	------------	--------	------------	-------	------------	--------	------------

\* \* \* FRICTIONLESS - ADIABATIC LINE 6 FLUID 10  
W DOT 7.37088-02 PRES 1.99993+02

TEMP 1.85500+03 PRES T 1.99995+02 TEMP T 1.85500+03

\* \* TURBINE 2 LINE IN = 6 LINE OUT = 7

PT IN	1.99995+02	TT IN	1.85500+03	WDOT 1	7.37088-02	CP TUR	5.48867-01	GAMMA	1.32700+00
PT OUT	1.00000+01	TT OUT	1.09382+03	W TURB	7.37088-02	AETUR	4.27170-02	DIAT	8.70000+00
PWNT	2.39638+04	ETA T	7.86047-01	CEFI	5.20000+00	CEFC	-8.60000+00	U/C	3.02326-01

\* \* \* FRICTIONLESS - ADIABATIC LINE 7 FLUID 10  
W DOT 7.37088-02 PRES 1.00000+01

TEMP 1.09382+03 PRES T 1.00246+01 TEMP T 1.09435+03

\* \* CHOKED EXIT 2 LINE 7  
WCHOKE 7.37088-02

PRES T 1.00246+01 TEMP T 1.09435+03 GAMMA 1.32700+00 ACHOKE 6.26660-01

\* \* TANK NO. 2 \* \* LGL 0 LGO 0 LWI 0 LWO 8

TIME	0.00000	P TANK	2.00000+01	T GAS	4.60000+02	T LIQ	4.60000+02	W LIQ	4.00000+04
M 1	1.06773+01	M 2	0.00000	ALPHA	0.00000	ENERGY	1.20669+04	RHO L	5.86501+01
DM1	0.00000	DM2	0.00000	DW NET	-4.75690+00	DU	-3.00179-01	UW IN	0.00000
CPI	3.45000+00	CP2	0.00000	RGAS 1	7.72630+02	RGAS 2	0.00000	V TANK	2.00000+03
DMVENT	0.00000	PVENT	0.00000	AVENT	0.00000	I-PP/P		I-PL/P	

\* \* \* FRICTIONLESS - ADIABATIC LINE 8 FLUID 3  
W DOT 4.75690+00 PRES 1.82319+01

TEMP 4.60000+02 PRES T 2.00000+01 TEMP T 4.60000+02

\* \* VALVE - LIQUID VALVE NO. 1 INLET LINE NO. 8 OUTLET LINE NO. 9 \* \*  
W DOT 4.75690+00 PRES I 1.82319+01 PRES O 1.73686+01

TEMP 4.60000+02 CD\*A 1.00000+00

\* \* \* FRICTIONLESS - ADIABATIC LINE 9 FLUID 3  
W DOT 4.75690+00 PRES 1.73686+01

TEMP 4.60000+02 PRES T 1.91366+01 TEMP T 4.60000+02

• • PUMP 1 DRIVEN BY TURBINE 1

LINE I	9	P IN	1.73686+01	T IN	4.60000+02	RPM	5.00000+04	W DOT	4.75690+00
LINE O	10	P OUT	4.72471+02	T OUT	4.66100+02	POWER	2.05404+04	EPSLN	2.58773+01
DENSTY	5.86501+01	CP	6.74300+01	GR	1.00000+00	R DIA	1.00000+00	R RPM	1.00000+00

• • • PIPL - LIQUID FUEL LINE NO. 10 FLUID -3 NODES 2 W DOT 4.75690+00

PROPERTIES									
LENGTH	5.00000+01	DIAM I	1.12024+00	DIAM O	1.12024+00	AREA I	1.46639+01	RGAS	5.25978+02
CP	6.75929+01	VISC	1.21122+03	COND	1.30818+01	NPR	2.25300+01	KA	0.00000
INLET CONDITIONS									
PRES	4.72471+02	TEMP	4.66100+02	DENS	5.84517+01	MACH	0.00000	VEL	1.18899+01
NRE	5.35651+04	NGR	0.00000	TWALL	4.66104+02	FRL	5.23414+03	UAO	9.97066+03
HRAD	0.00000	HO	0.00000	HI	6.79947+02	TOT P	0.00000	TOT T	4.66104+02
OUTLET CONDITIONS									
PRES	4.62471+02	TEMP	4.66100+02	DENS	5.84517+01	MACH	0.00000	VEL	1.18899+01
NRE	5.35651+04	NGR	0.00000	TWALL	4.66104+02	FRL	5.23414+03	UAO	9.97066+03
HRAD	0.00000	HO	0.00000	HI	6.79947+02	TOT P	0.00000	TOT T	0.00000

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• • VALVL - LIQUID VALVE NO. 3 INLET LINE NO. 10 OUTLET LINE NO. 11 • •

W DOT	4.75690+00	PRES I	4.62471+02	PRES O	4.52471+02	TEMP	4.66100+02	CD*A	2.94333+01
-------	------------	--------	------------	--------	------------	------	------------	------	------------

• • • FRICTIONLESS - ADIABATIC LINE 11 FLUID 3

W DOT	4.75690+00	PRES	4.52471+02	TEMP	4.66100+02	PRES T	4.54245+02	TEMP T	4.66100+02
-------	------------	------	------------	------	------------	--------	------------	--------	------------

• • TANK NO. 3 • • LGI 0 LGO 0 LWI 0 LWO 12

TIME	0.00000	P TANK	2.00000+01	T GAS	4.60000+02	T LIQ	4.60000+02	W LIQ	4.00000+04
M I	1.28141+01	M 2	0.00000	ALPHA	0.00000	ENERGY	1.44819+04	RHO L	9.56385+01
DM1	0.00000	DM2	0.00000	DW NET	-7.13536+00	DU	-2.76126+01	DQIN	0.00000
CP1	3.45000+00	CP2	0.00000	RGAS 1	7.72630+02	RGAS 2	0.00000	V TANK	2.00000+03
DMVENT	0.00000	PVENT	0.00000	AVENT	0.00000	1-PG/P		1-PL/P	

• • • FRICTIONLESS - ADIABATIC LINE 12 FLUID 4

W DOT	7.13536+00	PRES	1.41672+01	TEMP	4.60000+02	PRES T	2.00000+01	TEMP T	4.60000+02
-------	------------	------	------------	------	------------	--------	------------	--------	------------

• • VALVL - LIQUID VALVE NO. 2 INLET LINE NO. 12 OUTLET LINE NO. 13 • •

W DOT	7.13536+00	PRES I	1.41672+01	PRES O	1.13188+01	TEMP	4.60000+02	CD*A	1.00000+00
-------	------------	--------	------------	--------	------------	------	------------	------	------------

• • • FRICTIONLESS - ADIABATIC LINE 13 FLUID 4

W DOT	7.13536+00	PRES	1.13188+01	TEMP	4.60000+02	PRES T	1.71516+01	TEMP T	4.60000+02
-------	------------	------	------------	------	------------	--------	------------	--------	------------

• • PUMP 2 DRIVEN BY TURBINE 2

LINE 1 13	P IN	1.13188+01	T IN	4.60000+02	RPM	5.00000+04	W OUT	7.13536+00
LINE 0 14	P OUT	4.85473+02	T OUT	4.61061+02	POMER	2.139636+04	EP5LN	5.08756+01
DENSITY 4.00000+01	CP	2.00000+00	GM	1.00000+00	W DIA	1.00000+00	K RPM	1.00000+00

• • • PIPL - LIQUID OXIDZRLINE NO. 14 FLUID -4 NODES 2

W OUT 7.13536+00

PROPERTIES

LENGTH 5.00000+01	DIAM I	1.18846+00	DIAM O	1.18846+00	AREA I	1.55570+01	KGAS	1.55631+03
CP 2.00000+00	VISC	1.00000+05	COND	1.00000+01	NPR	7.20000+01	KA	0.00000

INLET CONDITIONS

PRES 4.85473+02	TEMP	4.61061+02	DENS	4.00000+01	MACH	0.00000	VEL	2.31556+01
NRE 9.17320+06	NGR	0.00000	TWALL	4.61067+02	FRL	2.13944+03	UAO	1.17706+05
HRAD 0.00000	HO	0.00000	HI	7.56611+03	TOT P	0.00000	TOT T	4.61067+02

OUTLET CONDITIONS

PRES 4.75473+02	TEMP	4.61061+02	DENS	9.55545+01	MACH	0.00000	VEL	2.31556+01
NRE 9.17320+06	NGR	0.00000	TWALL	4.61067+02	FRL	2.13944+03	UAO	1.17706+05
HRAD 0.00000	HO	0.00000	HI	7.56611+03	TOT P	0.00000	TOT T	0.00000

• • VALVE - LIQUID VALVE NO. 4 INLET LINE NO. 14 OUTLET LINE NO. 15 • •  
W OUT 7.13536+00 PRES I 4.75473+02 PRES O 4.65473+02

TEMP 4.61061+02 CD\*A 3.45305+01

• • • FRICTIONLESS - ADIABATIC LINE 15 FLUID 4

W OUT 7.13536+00 PRES 4.65473+02 TEMP 4.61061+02 PRES T 4.71306+02 TEMP T 4.61061+02

• • COMBUSTION CHAMBER NO. 2 • •

LINE 1 11 FLUID 3	PC FLO	3.50000+02	T LINE	4.66100+02	W OUT	4.75690+00	CD*A	9.19471+02
LINE 2 15 FLUID 4	PC FLO	3.50000+02	T LINE	4.61061+02	W OUT	7.13536+00	CD*A	1.57058+01
MR 1.50000+00	P CHAM	3.50000+02	T CHAM	5.54500+03	W NOZ	1.18923+01	THRT	3.50000+03
ISP 2.94309+02	CSTAR	5.74600+03	C F	1.71661+00	GAMMA	1.16600+00	CP	9.47500+01

CONSTRAINT VALUES

JUWSUM( 1 ) = 0.000000	TUR*10( 1 ) = -1.490116-08	CHOKEN( 1 ) = 1.490116-08	TUR*10( 2 ) = 0.000000
CHOKEN( 2 ) = 0.000000	PUMPHP( 1 ) = 0.000000	LINEDP( 10 ) = -1.066923-05	VALVDP( 3 ) = 0.000000
PUMPHP( 2 ) = 0.000000	LINEDP( 14 ) = 3.874302-07	VALVDP( 4 ) = 0.000000	CHAMB( 2 ) = -3.129244-07
CHAMPC( 2 ) = -1.937151-07	CHAPCO( 2 ) = -2.980232-08	CHTHRT( 2 ) = -1.490116-06	CMRDES( 2 ) = 0.000000

• • SUMMARY OF FUNCTIONAL CONSTRAINTS

AUTOMATIC IMPOSED SYSTEM CONSTRAINTS 9

OPTIONAL DESIGN CONSTRAINTS 7

TOTAL NUMBER OF CONSTRAINTS IMPOSED 16

## 8.0 SAMPLE CASE TWO - SENSITIVITY OF DESIGNED SYSTEM

To further illustrate built-in capabilities, the program was operated in a purely simulation mode. The system considered was the bipropellant thruster and feed system described in Section 7.0 (Sample Case One). The final design configuration of that case was used here. Within the tolerances provided by the convergence criteria, the two cases yielded identical system operating conditions. The results of this run form the nominal operating conditions.

The regulator pressure used for the nominal run was 200 psi. The response of the system to variations in the regulator pressure by plus and minus 10 percent, 20 percent, and 30 percent was then investigated by executing the program six additional times, each with a different value of the regulator pressure. Figures 8.1, 8.2, and 8.3 show the sensitivities of several pertinent system variables. The quantities displayed are percent variations from nominal of each dependent variable of the regulator pressure. These data indicate that the nominal operating point is stable and relatively insensitive to variations in the regulator setting. It is emphasized that a complete system balance was easily achieved at each operating point.

At the end of this section is a set of computer printouts showing the input data, partial derivative matrix, convergence summary, and the solution operating conditions for the plus 20 percent off-nominal case. Attention is called to the considerable similarity between the input data for this case and the input data for the design problem.

Figure 8.1 SAMPLE CASE TWO - SYSTEM SENSITIVITY

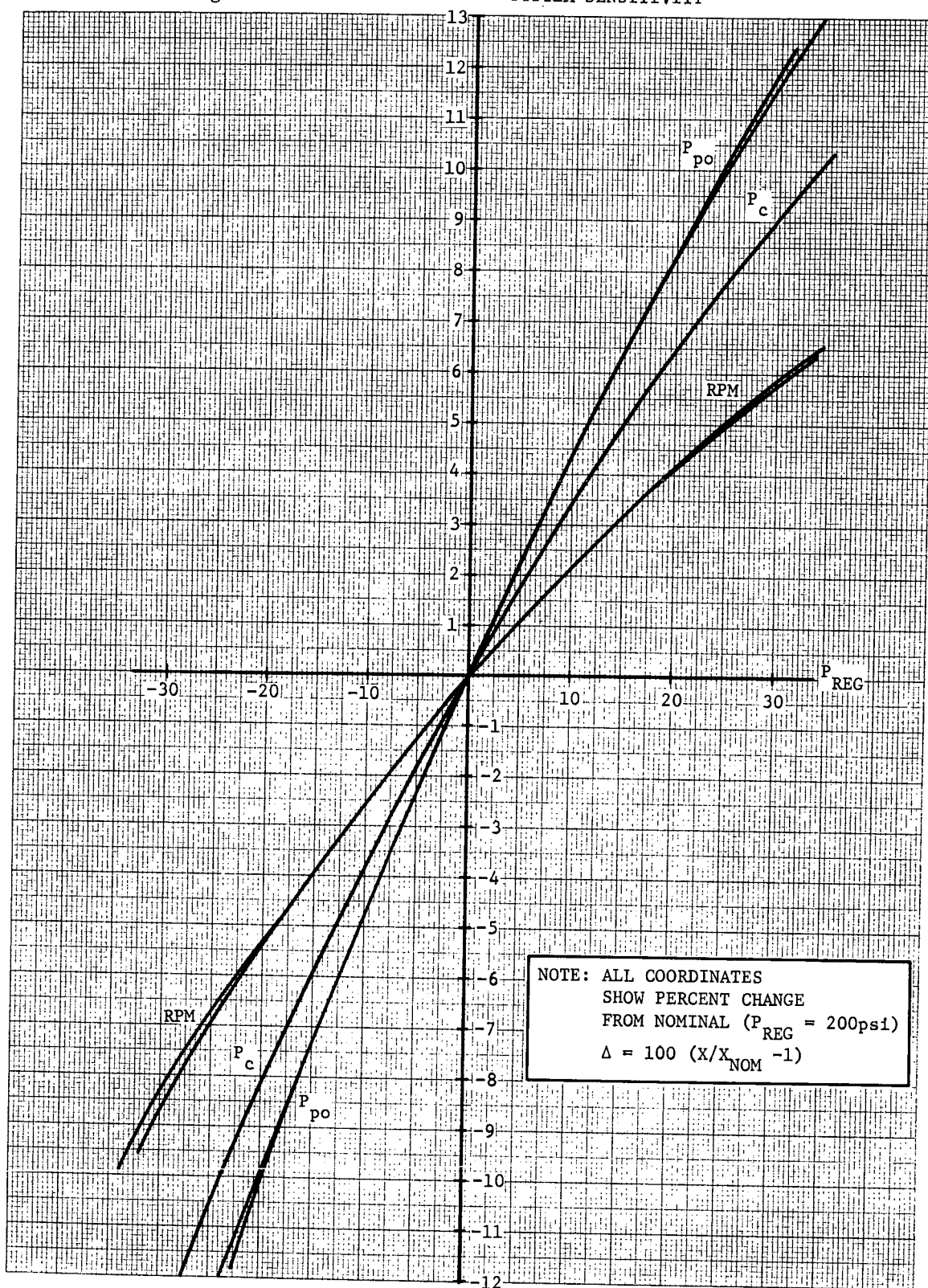


Figure 8.2 SAMPLE CASE TWO - SYSTEM SENSITIVITY

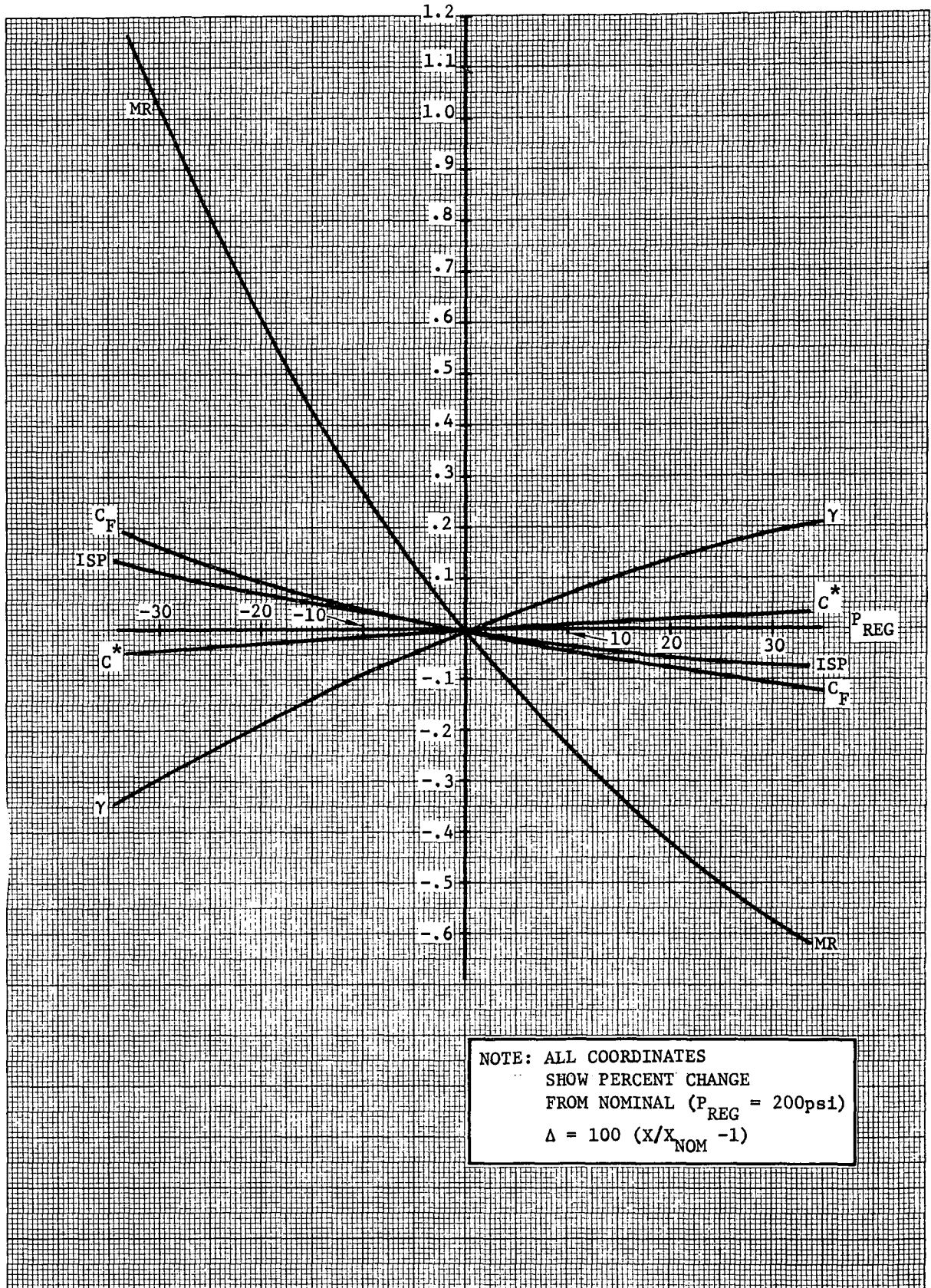
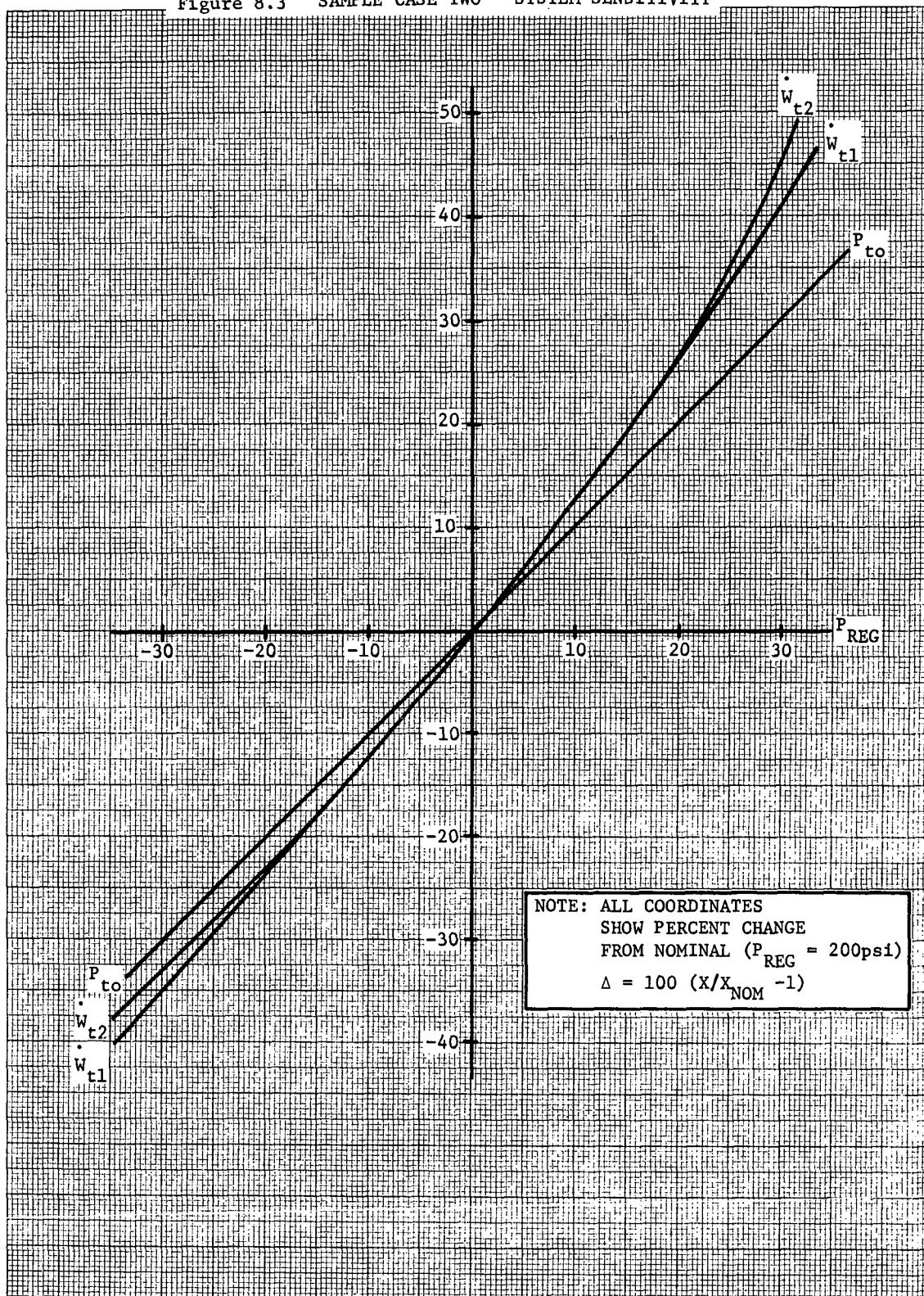


Figure 8.3 SAMPLE CASE TWO - SYSTEM SENSITIVITY





# SAMPLE CASE TWO - INPUT DATA

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* ACPS PROGRAM PROOF CASE 7/14/72
* MODIFICATION DATE : 8/03/72
*
* A-50 / N204 HIGH PC THRUSTOR
* DUAL TURBOPUMPS DRIVEN BY HYDROZINE MONO GG
* CHAMBER CONSTRAINTS - PC, F, MR
*
* PERFORMANCE MODE == NOMINAL CASE
* NOMINAL + 20 PERCENT
*
SYSCOM = TANK,1, LINE,1, PREG,1, LINE,2, CHAM,T, LINE,3, JUNCT,1,
        LINE,4, TURB,1, LINE,5, CHOKE,1,
        LINE,6, TURB,2, LINE,7, CHOKE,2,
        TANK,2, LINE,8, VALVL,1, LINE,9, PUMP,1, LINE,10, VALVL,3, LINE,11,
        TANK,3, LINE,12, VALVL,2, LINE,13, PUMP,2, LINE,14, VALVL,4, LINE,15,
        CHAM,2
*
STATE = WDOT,1, WDOT,4, WDOT,6, PTURBO,1, PTURBO,2
        RPMT,1, RPMT,2, WDOT,8, WDOT,12
*
* COMPONENT CONNECTIONS
LDWO = 1,8,12
LVA1 = 8,12,10,14
LVA0 = 9,13,11,15
LPRI = 1
LPRO = 2
LCHA1 = 2,11
LCHA2(2) = 15
LCHAM = 3
LIJUI = 3
LOJUI = 4,6
LTURB1 = 4,6
LTURB0 = 5,7
LCHOKE = 5,7
LPUMP1 = 9,13
LPUMP0 = 10,14
*
* COMPONENT SPECIFICATIONS
*
* TANKS
VTANK = 20.,2000.,2000.
PTANK = 300.,20.,20.
TTANK = 3R460.
WOL = 400.,4.E4,4.E4
TLIQ = 3R460.
CPI = 3R3.45
RI = 3R772.83
*

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• LINES

LTYPE = 15R4  
 LTYPE(10) = 1  
 LTYPE(14) = 1  
 DIALI = 15R1.  
 DIALI(3) = 5R3.  
 DIALI(10) = 1.120237  
 DIALI(14) = 1.188464  
 XLENG(10) = 50.  
 XLENG(14) = 50.  
 NPLINE = 2R-6,5R10,4R-3,4R-4

• TURBINES

CEF1 = 2R5.2  
 CEF2 = 2R-8.6  
 RPMD = 5.E4  
 DIAT = 8.7, 8.7  
 AEFTUR(1) = .03661470  
 AEFTUR(2) = .04271712  
 ACHOKE(1) = .5374620  
 ACHOKE(2) = .6266706

• PUMP

ITURB = 1,2  
 GR = 1.  
 RPMD = 2R5.E4  
 RDPUMP(1) = 1.  
 RDPUMP(2) = 1.  
 POW0 = 2R.147E5, POW1 = 2R.110E4, POW2 = 2R.250E2, POW3 = 2R.391  
 PWO = 2R.417E3, PW1 = 2R.801E1, PW2 = 2R-.169E1 \* PUMP CURVES

• VALVES

CDAV = 1., 1.  
 CDAV(3) = .2943330  
 CDAV(4) = .3453054  
 PRE(1) = 200.  
 PRE(1) = 240.

• COMBUSTION CHAMBERS

PATM = 0.  
 DISOC(1) = 0.8 \* MONO GG DISSOC  
 ARINJ1(1) = .4  
 ARINJ1(2) = .09178224  
 ARINJ2(2) = .1562376  
 AREAT(2) = 5.825422  
 ERATIO(2) = 40.  
 LAMDA(2) = .9806 \* 16 DEG DIV. LOSS  
 ECSTAR(2) = .96 \* C-STAR EFFICIENCY  
 ECSTAR(1) = .93 \* C-STAR EFFICIENCY - GG  
 ECF(2) = .95 \* CF EFFICIENCY

•  
• ESTIMATE OF STATE VARIABLES

WDOT(1) = .14  
WDOT(4) = .06  
WDOT(6) = .07  
WDOT(8) = 4.7  
WDOT(12) = 7.1

RPMT(1) = 5.E4  
RPMT(2) = 5.E4  
PTURBO = 10., 10.

•  
• EQUATION SOLVER

MAXIT = 30  
DYLIM = .2  
DYUP = .2  
YBNDL = 0.  
EPSDY = 1.E-6  
EPSZ = 1.E-6

•  
•  
•  
•  
ENDCAS

SAMPLE CASE TWO-

PARTIAL DERIVATIVE MATRIX J= 1 TO 9

100	1	-.51852	.22222	.25926	.00000	.00000	.00000	.00000	.00000	.00000
	2	-.00004	-.75078	.00000	.00000	.00000	.00000	.00000	.00000	.00000
	3	-.00001	-.88620	.00000	.81833	.00000	.00000	.00000	.00000	.00000
	4	-.00004	.00000	-.75079	.00000	.00000	.00000	.00000	.00000	.00000
	5	-.00002	.00000	-.88546	.00000	.81765	.00000	.00000	.00000	.00000
	6	-.00001	-.89247	.00000	.18736	.00000	2.36129	.00000	.28337	.00000
	7	-.00002	.00000	-.89109	.00000	.18708	.00000	2.24148	.00000	.40627
	8	.00000	.00000	.00000	.00000	.00000	2.36681	-2.55095	-.59057	.65340
	9	.00000	.00000	-.00000	.00000	.00000	1.19765	1.22409	-.66240	-.94540

# SAMPLE CASE TWO - CONVERGENCE SUMMARY

NON-LINEAR SOLUTION IT = 5 FNORM = .20366-06

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I	X	Y	Y PARTIAL	X REF	DY	Z
1	.173149+00	1.23678	1.23678	.1400+00	.0000	.0000
2	.799151-01	1.33192	1.22000	.6000-01	.0000	.0000
3	.932342-01	1.33192	1.22000	.7000-01	.0000	.0000
4	.119999+02	1.19999	1.20002	.1000+02	-.2571-06	.0000
5	.119999+02	1.19999	1.20004	.1000+02	-.3565-06	-.2980-07
6	.520755+05	1.04151	1.00000	.5000+05	-.6215-05	.1326-05
7	.520480+05	1.04096	1.00000	.5000+05	-.4046-05	.9537-06
8	.507408+01	1.07959	1.00000	.4700+01	-.1202-05	.7004-06
9	.757934+01	1.06751	1.00000	.7100+01	-.6707-05	.4470-06

SOLUTION ELAPSED TIME = .029 MINUTES

# SAMPLE CASE TWO - COMPUTER SOLUTION

## STATE VARIABLES

WDOT ( 1 ) = 1.731493-01 WDOT ( 4 ) = 7.991511-02 WDOT ( 6 ) = 9.323423-02 PTURBO( 1 ) = 1.199990+01  
 PTURBO( 2 ) = 1.199990+01 RPMT ( 1 ) = 5.207554+04 RPMT ( 2 ) = 5.204803+04 WDOT ( 8 ) = 5.074084+00  
 WDOT ( 12 ) = 7.579343+00

• • TANK NO. 1 • • LGI 0 LGO 0 LWI 0 LWO 1

TIME	0.00000	P TANK	3.00000+02	T GAS	4.60000+02	T LIQ	4.60000+02	W LIQ	4.00000+02
M 1	1.52529+00	M 2	0.00000	ALPHA	0.00000	ENERGY	1.72380+03	RHO L	5.37052+01
DM1	0.00000	DM2	0.00000	DW NET	-1.73149-01	DU	-1.78987-01	DQIN	0.00000
CP1	3.45000+00	CP2	0.00000	RGAS 1	7.72830+02	RGAS 2	0.00000	V TANK	2.00000+01
DMVENT	0.00000	PVENT	0.00000	AVENT	0.00000	1-PG/P		1-PL/P	

• • • FRICTIONLESS - ADIABATIC LINE 1 FLUID 6  
 W DOT 1.73149-01 PRES 2.99998+02 TEMP 4.60000+02 PRES T 3.00000+02 TEMP T 4.60000+02

• • • • REGULATOR NO. 1 • • LINE NO. INLET 1 OUTLET 2

PA	2.99998+02	TA	4.60000+02	FUNC	0.00000	FUNCP	0.00000	RHO2	5.37052+01
PB	2.40000+02	TB	4.60000+02	WDOT	1.73149-01	IPROP	6		
ENTHA	0.00000	ENTHB	0.00000						

• • • FRICTIONLESS - ADIABATIC LINE 2 FLUID 6  
 W DOT 1.73149-01 PRES 2.40000+02 TEMP 4.60000+02 PRES T 2.40003+02 TEMP T 4.60000+02

• • COMBUSTION CHAMBER NO. 1 • •

LINE 1	2	FLUID 6	PC FLO	2.39992+02	T LINE	4.60000+02	W DOT	1.73149-01	CD*A	4.00000-01
LINE 2	0	FLUID 4	PC FLO	3.72480+02	T LINE	0.00000	W DOT	7.57934+00	CD*A	1.56238-01
MR	8.00000-01		P CHAM	2.39992+02	T CHAM	1.85500+03	W NOZ	1.73149-01	THRT	0.00000
ISP	2.94155+02		CSTAR	1.67000+03	C F	1.71535+00	GAMMA	1.32700+00	CP	4.94003-01

• • • FRICTIONLESS - ADIABATIC LINE 3 FLUID 10  
 W DOT 1.73149-01 PRES 2.39985+02 TEMP 1.85499+03 PRES T 2.39992+02 TEMP T 1.85500+03

• • • • JUNCTION NO. 1

LINE 3	IN	W DOT	1.73149-01	PRES T	2.39992+02	TEMP T	1.85500+03	PRES	2.39985+02
LINE 4	OUT	W DOT	7.99151-02	PRES T	2.39992+02	TEMP T	1.85500+03	PRES	
LINE 6	OUT	W DOT	9.32342-02	PRES T	2.39992+02	TEMP T	1.85500+03	PRES	

• • • FRICTIONLESS - ADIABATIC LINE 4 FLUID 10  
 W DOT 7.99151-02 PRES 2.39991+02 TEMP 1.85500+03 PRES T 2.39992+02 TEMP T 1.85500+03

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* * TURBINE 1 LINE IN = 4 LINE OUT = 5
PT IN 2.39992+02 TT IN 1.85500+03 WDOT 1 7.99151-02 CP TUR 4.94003-01 GAMMA 1.32700+00
PT OUT 1.19999+01 TT OUT 1.09382+03 W TURB 7.99151-02 AEFTUR 3.66147-02 DIAT 8.70000+00
PDWT 2.33836+04 ETA T 7.86047-01 CEF1 5.20000+00 CEF2 -8.60000+00 U/C 3.02326-01

* * * FRICTIONLESS - ADIABATIC LINE 5 FLUID 10
W DOT 7.99151-02 PRES 1.19999+01 TEMP 1.09382+03 PRES T 1.20216+01 TEMP T 1.09421+03

* * CHOKED EXIT 1 LINE 5
WCHOKE 7.99151-02 PRES T 1.20216+01 TEMP T 1.09421+03 GAMMA 1.32700+00 ACHOKE 5.37462-01

* * * FRICTIONLESS - ADIABATIC LINE 6 FLUID 10
W DOT 9.32342-02 PRES 2.39990+02 TEMP 1.85500+03 PRES T 2.39992+02 TEMP T 1.85500+03

* * TURBINE 2 LINE IN = 6 LINE OUT = 7
PT IN 2.39992+02 TT IN 1.85500+03 WDOT 1 9.32342-02 CP TUR 4.94003-01 GAMMA 1.32700+00
PT OUT 1.19999+01 TT OUT 1.09382+03 W TURB 9.32342-02 AEFTUR 4.27171-02 DIAT 8.70000+00
PDWT 2.72808+04 ETA T 7.86047-01 CEF1 5.20000+00 CEF2 -8.60000+00 U/C 3.02326-01

* * * FRICTIONLESS - ADIABATIC LINE 7 FLUID 10
W DOT 9.32342-02 PRES 1.19999+01 TEMP 1.09382+03 PRES T 1.20294+01 TEMP T 1.09435+03

* * CHOKED EXIT 2 LINE 7
WCHOKE 9.32342-02 PRES T 1.20294+01 TEMP T 1.09435+03 GAMMA 1.32700+00 ACHOKE 6.26671-01

* * TANK NO. 2 * * LGI 0 LGO 0 LWI 0 LWO 8
TIME 0.00000 P TANK 2.00000+01 T GAS 4.60000+02 T LIQ 4.60000+02 W LIQ 4.00000+04
M 1 1.06773+01 M 2 0.00000 ALPHA 0.00000 ENERGY 1.20670+04 RHO L 5.86501+01
DM1 0.00000 DM2 0.00000 DW NET -5.07408+00 DU -3.20195-01 DQIN 0.00000
CP1 3.45000+00 CP2 0.00000 RGAS 1 7.72830+02 RGAS 2 0.00000 V TANK 2.00000+03
DMVENT 0.00000 PVENT 0.00000 AVENT 0.00000 1-PG/P 1-PL/P

* * * FRICTIONLESS - ADIABATIC LINE 8 FLUID 3
W DOT 5.07408+00 PRES 1.84074+01 TEMP 4.60000+02 PRES T 2.00000+01 TEMP T 4.60000+02

* * VALVL - LIQUID VALVE NO. 1 INLET LINE NO. 8 OUTLET LINE NO. 9 * *
W DOT 5.07408+00 PRES 1 1.84074+01 PRES 0 1.74251+01 TEMP 4.60000+02 CD*A 1.00000+00

* * * FRICTIONLESS - ADIABATIC LINE 9 FLUID 3
W DOT 5.07408+00 PRES 1.74251+01 TEMP 4.60000+02 PRES T 1.94367+01 TEMP T 4.60000+02

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\* \* PUMP 1 DRIVEN BY TURBINE 1

LINE I 9	P IN	1.74251+01	T IN	4.60000+02	RPM	5.20755+04	W DOT	5.07408+00
LINE O 10	P OUT	5.12094+02	T OUT	4.66468+02	POWER	2.33836+04	EPSLN	2.63545+01
DENSTY 5.86501+01	CP	6.74300+01	GR	1.00000+00	R DIA	1.00000+00	R RPM	1.04151+00

\* \* PIPL \* \* LIQUID FUEL LINE NO. 10 3 NODES WDOT 5.07408

PROPERTIES

LENGTH 5.00000+01	DIAM I	1.12024+00	DIAM O	1.12024+00	AREA I	1.46639+01	RGAS	5.26554+02
CP 6.76027+01	VISI	1.20575+03	COND	1.30820+01	NPR	2.24309+01	KA	0.00000

INLET CONDITIONS

PRES 5.12094+02	TEMP	4.66468+02	DENS	5.84397+01	MACH	0.00000	VEL	1.26853+01
NRE 5.73963+04	NGR	0.00000	TWALL	4.66473+02	FRL	5.15031+03	UAD	1.05189+04
HRAD 0.00000	HO	0.00000	HI	7.17331+02	TOT P	0.00000	TOT T	4.66473+02

OUTLET CONDITIONS

PRES 5.00896+02	TEMP	4.66468+02	DENS	5.84397+01	MACH	0.00000	VEL	1.26853+01
NRE 5.73963+04	NGR	0.00000	TWALL	4.66473+02	FRL	5.15031+03	UAD	1.05189+04
HRAD 0.00000	HO	0.00000	HI	7.17331+02	TOT P	0.00000	TOT T	0.00000

\* \* VALVE - LIQUID VALVE NO. 3 INLET LINE NO. 10 OUTLET LINE NO. 11 \* \*

W DOT 5.07408+00	PRES I	5.00896+02	PRES O	4.89516+02	TEMP	4.66468+02	CO-A	2.94333+01
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\* \* \* FRICTIONLESS - ADIABATIC LINE 11 FLUID 3

W DOT 5.07408+00	PRES	4.89516+02	TEMP	4.66468+02	PRES T	4.91534+02	TEMP T	4.66468+02
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\* \* TANK NO. 3 \* \* LGI 0 LGO 0 LWI 0 LWO 12

TIME 0.00000	P TANK	2.00000+01	T GAS	4.60000+02	T LIQ	4.60000+02	W LIQ	4.00000+04
M I 1.28142+01	M 2	0.00000	ALPHA	0.00000	ENERGY	1.44819+04	KHO L	9.56385+01
DM1 0.00000	DM2	0.00000	OW NET	-7.57934+00	DU	-2.93308+01	QIN	0.00000
CPI 3.45000+00	CP2	0.00000	RGAS 1	7.72830+02	RGAS 2	0.00000	V TANK	2.00000+03
OHVENT 0.00000	PVENT	0.00000	AVENT	0.00000	1-PG/P		1-PL/P	

\* \* \* FRICTIONLESS - ADIABATIC LINE 12 FLUID 4

W DOT 7.57934+00	PRES	1.47898+01	TEMP	4.60000+02	PRES T	2.00000+01	TEMP T	4.60000+02
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\* \* VALVE - LIQUID VALVE NO. 2 INLET LINE NO. 12 OUTLET LINE NO. 13 \* \*

W DOT 7.57934+00	PRES I	1.47898+01	PRES O	1.15759+01	TEMP	4.60000+02	CO-A	1.00000+00
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\* \* \* FRICTIONLESS - ADIABATIC LINE 13 FLUID 4

W DOT 7.57934+00	PRES	1.15759+01	TEMP	4.60000+02	PRES T	1.81572+01	TEMP T	4.60000+02
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• • PUMP 2 DRIVEN BY TURBINE 2

LINE 1 13	P IN	1.15759+01	T IN	4.60000+02	RPM	5.20480+04	W DOT	7.57934+00
LINE 0 14	P OUT	5.26634+02	T OUT	4.61121+02	POWER	2.72809+04	EPSLN	5.15148+01
DENSTY 4.00000+01	CP	2.00000+00	GR	1.00000+00	R DIA	1.00000+00	R RPM	1.04096+00

• • PIPL • • LIQUID OXIDZR LINE NO. 14 4 NODES WDOT 7.57934

PROPERTIES									
LENGTH	5.00000+01	DIAM I	1.18846+00	DIAM O	1.18846+00	AREA I	1.55570+01	RGAS	1.55631+03
CP	2.00000+00	VISC	1.00000+05	COND	1.00000+01	NPR	7.20000+01	KA	0.00000

INLET CONDITIONS									
PRES	5.26634+02	TEMP	4.61121+02	DENS	4.00000+01	MACH	0.00000	VEL	2.45964+01
NRE	9.74399+06	NGR	0.00000	TWALL	4.61127+02	FRL	2.12529+03	UAO	1.23529+05
HRAD	0.00000	HO	0.00000	HI	7.94046+03	TOT P	0.00000	TOT T	4.61127+02

OUTLET CONDITIONS									
PRES	5.15425+02	TEMP	4.61121+02	DENS	9.55497+01	MACH	0.00000	VEL	2.45964+01
NRE	9.74399+06	NGR	0.00000	TWALL	4.61127+02	FRL	2.12529+03	UAO	1.23529+05
HRAD	0.00000	HO	0.00000	HI	7.94046+03	TOT P	0.00000	TOT T	0.00000

• • VALVL - LIQUID VALVE NO. 4 INLET LINE NO. 14 OUTLET LINE NO. 15 • •

W DOT	7.57934+00	PRES I	5.15425+02	PRES O	5.04142+02	TEMP	4.61121+02	CD•A	3.45305+01
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• • • FRICTIONLESS - ADIABATIC LINE 15 FLUID 4

W DOT	7.57934+00	PRES	5.04142+02	TEMP	4.61121+02	PRES T	5.10723+02	TEMP T	4.61121+02
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• • COMBUSTION CHAMBER NO. 2 • •

LINE 1 11	FLUID 3	PC FLO	3.72480+02	T LINE	4.66468+02	W DOT	5.07408+00	CD•A	9.17822+02
LINE 2 15	FLUID 4	PC FLO	3.72480+02	T LINE	4.61121+02	W DOT	7.57934+00	CD•A	1.56238+01
MR	1.49374+00	P CHAM	3.72480+02	T CHAM	5.54800+03	W NOZ	1.26534+01	THRT	3.72206+03
ISP	2.94155+02	CSTAR	5.74721+03	C F	1.71535+00	GAMMA	1.16957+00	CP	9.29170+01

CONSTRAINT VALUES

JUWSUM( 1 ) = 0.000000	TURWIO( 1 ) = 0.000000	CHOKEW( 1 ) = 0.000000	TURWIO( 2 ) = 0.000000
CHOKEW( 2 ) = -2.980232-08	PUMPMP( 1 ) = 1.326203-06	PUMPMP( 2 ) = 9.536743-07	CHAMBI( 2 ) = 7.003546-07
CHAMPC( 2 ) = 4.470348-07			

• • SUMMARY OF FUNCTIONAL CONSTRAINTS

AUTOMATIC	IMPOSED SYSTEM CONSTRAINTS	9
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OPTIONAL	DESIGN CONSTRAINTS	0
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TOTAL NUMBER OF CONSTRAINTS IMPOSED	9
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9.0 NOMENCLATURE

<u>Symbols</u>	<u>Description</u>	<u>Units</u>
A	Area	in <sup>2</sup>
A	Constraint function (3.5)	
a	General coefficients	
b	General coefficients	
C	Isentropic spouting velocity (4.8)	ft/sec
C	General constant	
C*	Characteristic exit velocity (4.7)	ft/sec
C <sub>d</sub>	Discharge coefficient	-
C <sub>p</sub>	Specific heat at constant pressure	B/lbm-°R
D	Diameter (line, turbine, pump)	in
F	Thrust (4.7)	lbf
f	Friction factor (4.1)	-
f	General function	-
f	Tabular correction function (4.10)	-
F,f	Constraint function	-
g	Acceleration	ft/sec <sup>2</sup>
g <sub>c</sub>	Gravitational constant	lbm-sec <sup>2</sup> / lbf-ft
G	General function (3.3)	-
h	Enthalpy	B
H	Heat transfer coefficient	B/ft <sup>2</sup> -°R
I <sub>sp</sub>	Specific impulse (4.7)	lbf
K	Thermal conductivity	B/ft-hr-°R
L	Length	ft
M	Mach number	-
m	Mass of gas (4.4)	lbm
$\dot{m}$	Gas Mass flowrate (4.4)	lbm/sec
MR	Mixture ratio (4.7)	-
N	Rotational speed	RPM
N,n	Number of state variables and constraint equations	-
N <sub>Gr</sub>	Grashoff number	-
N <sub>Pr</sub>	Prandtl number	-

Note: Numbers in parentheses refer to Section in which symbol has local usage.

# NOMENCLATURE (Continued)

<u>Symbols</u>	<u>Description</u>	<u>Units</u>
$N_{Re}$	Reynolds number	-
P	Partial derivative matrix (3.5)	-
P,p	Pressure	psi
P	Power	ft-lbf/sec
Q	Heat added (4.4)	B
R	Radius	in
R	Gas constant	ft-lbf/lbm-°R
S	Entropy	B/lbm-°R
SV	Specific volume (4.10)	in <sup>3</sup> /lbm
T	Temperature	°R
th	Wall thickness (4.10)	in
u	General system variable (3.3)	-
u	Turbine tip speed (4.8)	ft/sec
u	Internal energy (4.4)	B
V	Gas velocity	ft/sec
$\dot{W}, \dot{w}$	Mass flow rate	lbm/sec
X	Dimensional state variable (3.5)	-
X	Fluid quality (4.10)	-
y	General system variable (3.3)	-
y	Non-dimensional state variable (3.5)	-
$\alpha$	Angle (4.1)	-
$\alpha$	Mass ratio (4.4)	-
$\gamma$	Specified heat ratio ( $C_p/C_v$ )	-
$\mu$	Fluid viscosity	lbm/ft-sec
$\eta$	Efficiency	-
$\lambda$	Divergence loss factor (4.7)	-
$\epsilon$	Convergence criterion (3.5)	-
$\epsilon$	Nozzle expansion ratio (4.7)	-
$\epsilon$	Wall emissivity (4.1)	-
$\Delta t$	Incremental change	-
$\Delta( )$	Time increment	-
$\rho$	Mass density	lbm/ft <sup>3</sup>
$\phi$	General property functions	-

<u>Subscripts</u>	<u>Description</u>
a	Atmospheric condition
a	Outside flow path (4.10)
A	Inlet to line segment (4.1)
b	Inside flow path (4.10)
B	Bulk fluid conditions (4.10)
B	Outlet from segment line (4.2)
c	Chamber
c, crit	Choking condition
D	Design condition
E	Environmental condition
e, eff.	Effective
G	Gaseous state
G	Gear
h	Hydraulic (4.10)
HX	Heat exchanger
i	At inlet of component
i	Constraint equation index (3.5)
i	Inner (4.1)
inj	Injector
j	State variable index (3.5)
J	Junction
L	Liquid state
L, 1	Line
max	Maximum
min	Minimum
noz	Nozzle conditions
o	At outlet of component
o	Initial estimate
o	Outer (4.1)
opt	Optimum expansion ratio (4.7)
P	Pump
ref	Reference value
reg	Regulator
sat	At saturated conditions (4.10)

<u>Subscripts (continued)</u>	<u>Description</u>
t	Total (stagnation conditions)
T	Turbine
tank	Tank component
V	Valve
v	Vent
w	Pertaining to flow
w	Wall (4.1)
1	Initial gaseous species (4.4)
2	Second gaseous species (4.4)
1,2,3,...	Refers to successive estimates (3.5)

<u>Superscripts</u>	<u>Description</u>
k	Iteration counter (3.5)
l	Pertaining to current iteration (3.5)
o	Pertaining to previous iteration or initial condition (3.5)

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## APPENDIX A Program Elements

The list below shows every program element associated with the steady-state Attitude Control Propulsion System simulation program. A description of each element follows the list.

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Note: On the following pages in Appendix A, underlining of variables appearing in the "Users Inputs" list designates input requirements for proper subroutine operation. "User Inputs" refer to ACPs program options. "External References" refer to ACPs program elements and do not include references to subprograms available on the Univac 1108 system library.

## A1.0 Configuration Generator - PREPRC

Description: The PREPRC program generates the computer code forming the dynamic subroutine GATHER to reflect the user defined system configuration. The configuration is defined through the SYSCOM array by listing the required component module names and identification numbers in the desired sequence of execution. PREPRC verifies the input names against a table of the legal component module names and writes, on I/O unit B, card images of Fortran CALL statements referencing these modules. Similarly, program variables are designated as state variables by listing the names of desired state variables in the input array STATE. PREPRC generates statements equating the appropriate program variables to the elements of the state vector, X. Initialization of X also is performed in PREPRC.

Logical unit B, which can be either a Fastran or magnetic tape unit, is used to interface with the main program SSPIPE. PREPRC writes two files, the first of which contains the generated source code for GATHER. Card data input to PREPRC is loaded into the common block INDATA and is made available to SSPIPE through the second file on unit B.

Usage:    ▽ XQT PREPRC

PREPRC is executed prior to SSPIPE to generate the necessary structure of GATHER. However, PREPRC need not be executed if an interface tape is available from a prior simulation of a system having the same configuration and set of state variables.

Referenced by:    User

External References:    TRWLOD, QQPCFW

Common Blocks:    INDATA

User Inputs: SYSCOM, STATE, initial estimate of state variables, component connections, component specifications, equation solver control data, comment cards.

Printed Output: Images of dynamic statements generated in GATHER, e.g.,

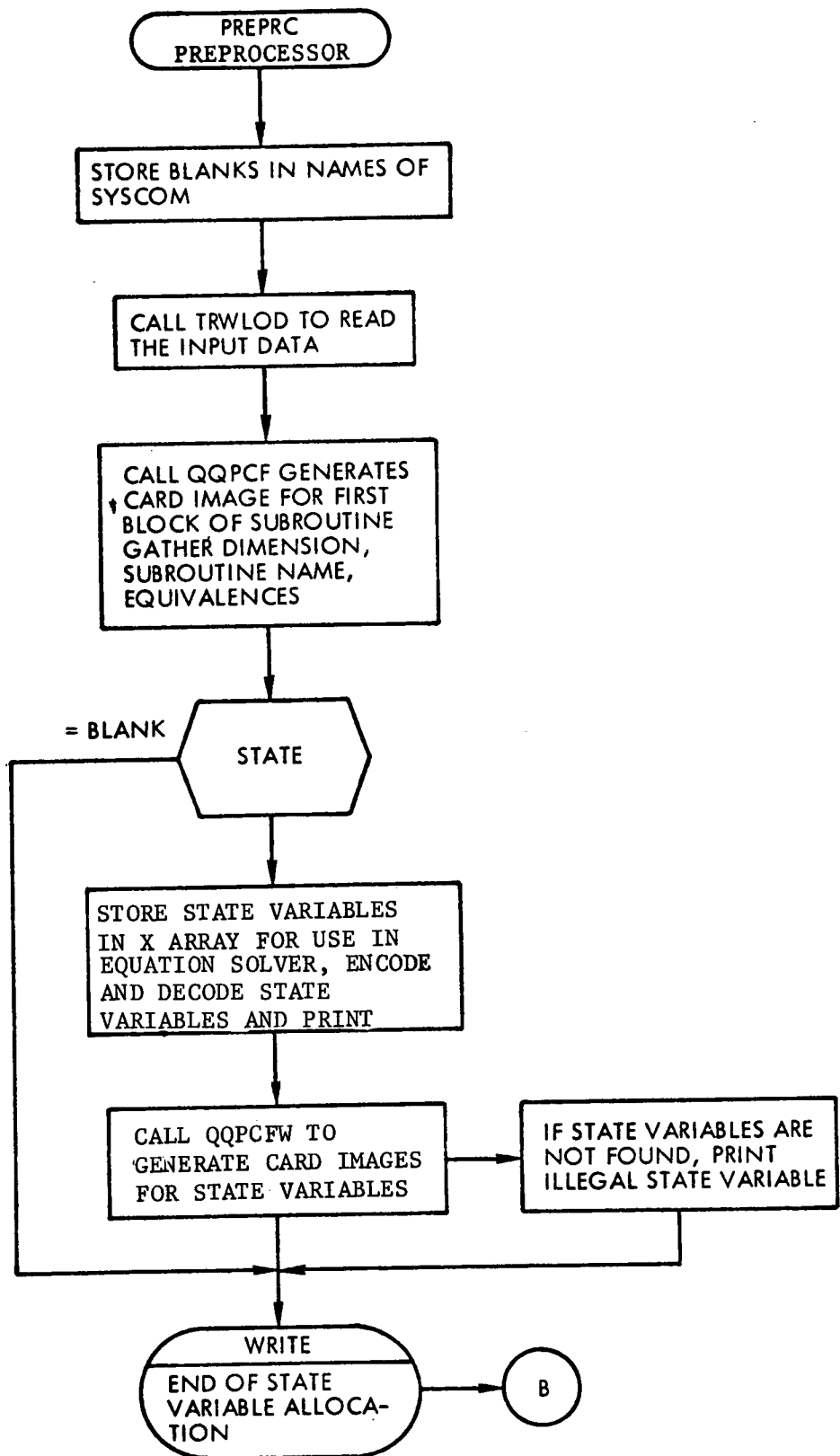
```
      WDOT(1) = X(1)
      .
      .
      END OF STATE VARIABLE ALLOCATION

      CALL TANK(1)

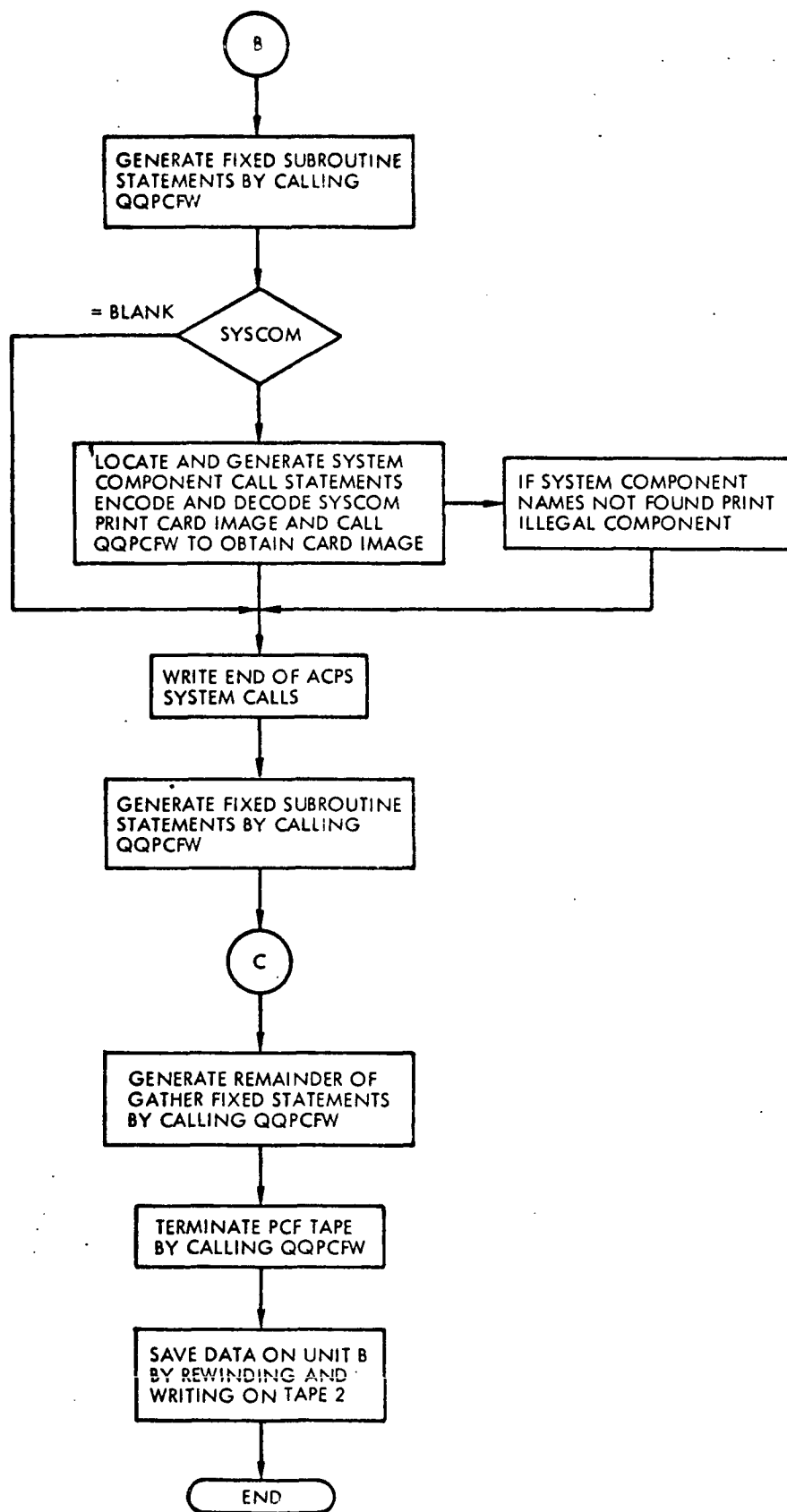
      CALL LINE(1)
      .
      .
      END OF ACPS SYSTEM CALLS
```

Other Output: Two files on I/O logical unit B containing subroutine GATHER and common block INDATA. B must be assigned to Fastran or magnetic tape.

Flow Chart: A function flow chart of PREPRC is presented on the next two pages.



FLOW CHART PREPRC



FLOW CHART PREPRC

## A2.0 ACPS Main Program - SSPIPE

Description: SSPIPE is the driver for the ACPS simulation program. The INDATA common block containing data loaded during execution of PREPRC and the state variable initial estimates are read from the second file of I/O unit B. TRWLOD is called so that additional input data may be loaded, over-  
laying any previously existing data. Execution then transfers to the equation solver, NLSOLV, which obtains an operating point of the system. Upon return, a final reference to GATHER with the print flag on generates the detailed solution printout. If a quasi-steady operating history is requested, NLSOLV and GATHER are called repeatedly with advancing values of the simulation time. Execution terminates upon reaching the stop time. The default value (zero) results in a single system operating point.

Usage: ▽ XQT SSPIPE

Referenced by: User

External References: TRWLOD, RESET, CLOCK, NLSOLV, GATHER

Common Blocks: INDATA

User Inputs: PREPRC interface tape (Fastran) assigned to I/O unit B, DELT, TIMEND, component connections, component specifications, equation solver control data, comment cards. SYSCOM and STATE cannot be loaded. State variable estimates can be loaded through array X.

Printed Output: "SOLUTION ELAPSES TIME xx.xxx MINUTES"

### A3.0 System Subroutines

The elements described in this section of Appendix A relate to the equation solver which is the backbone of the ACPs simulation program. The basic element of this system is subroutine NLSOLV which, by employing a multi-dimensional Newton-Raphson iteration method, seeks a solution vector which satisfies the various physical constraints necessary to the simulation. To implement this method, various autonomous procedures are performed in lower level subroutines. For example, GATHER references the component modules, PARTAL generates the partial derivative matrix, and GJR solves the resulting linearized problem.

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### A3.1 Subroutine BDATA

Description: BDATA is a BLOCK DATA element which contains physical constants and a number of default values to back up the user input data for the SSPIPE program and supporting component modules.

Usage: BLOCK DATA

Referenced by: Fortran system at time of loading

External References: None

Common Blocks: INDATA, CONS

User Inputs: None

Printed Output: None



### A3.2 Subroutine FCONCT

Description: This subroutine imposes all constraints specified during the execution of the component modules. Upon first entry (per program iteration) the constraint counters are initialized and the names and current values of the state variables are displayed from the array STATE. Successive entries are made from the component modules as constraints become necessary at which time the constraint counters are updated, and the constraint variable  $F(IC) = 1 - VAL/REF$  is computed and stored along with the corresponding descriptive name. Upon completion of the pass through the component modules, a call from GATHER through the entry point ECONCT causes the current constraint values to be displayed. A test for equality of the number of imposed constraints with the number of state variables is made, and an error message is printed if unequal. The print flag RFLAG is decremented by one.

Usage:      CALL ICØNCT(X) (from GATHER)  
                 CALL FCØNCT(N,VAL,REF,IFNAME, K1)  
                 CALL ECØNCT(FF) (from GATHER)

Referenced by: All component modules as required.

External References: None

Common Blocks: INDATA

User Inputs: None

Printed Output: 1) Current state variable values in order specified by input array STATE  
                    2) Current constraint function values in order of imposition defined internally  
                    3) Constraint summary if print flag is on.

### A3.3 Function FNORM

Description: FNORM computes the norm of the constraint (error or residual) vector, Z.

Usage: ZFNORM = FNORM(Z,N)

Referenced by: NLSOLV, PARTIAL

External References: None

User Inputs: None

Printed Output: None

#### A3.4 Subroutine GATHER

Description: The GATHER subroutine is the dynamic element generated by a prior execution of the preprocessor (PREPRC) using the system definition data contained in the arrays SYSCOM and STATE as provided by the user. It is executed once for each program iteration and controls the sequential execution of the required component modules. Prior to these CALLS, GATHER loads the current values of the state vector elements into the corresponding program variables.

Usage: CALL GATHER(N,Y,F,XR)

Referenced by: SSPIPE, NLSOLV, PARTAL

External References: ICONCT, ECONCT, all required component modules.

Common Blocks: INDATA

User Inputs: None

Printed Output: None

### A3.5 Subroutine GJR

Description: GJR is a matrix mathematics module which was obtained from the Univac 1108 MATH-PACK library. This subroutine solves systems of simultaneous linear equations, computes determinants, or inverts a matrix, or any combination of these three by using a Gauss-Jordan elimination technique with column pivoting. As presently formulated, the ACPS program employs only the inversion option. However, since use of other options may be appropriate for future program modifications, the more detailed Univac documentation is reproduced here.

Usage: CALL GJR(A,NC,NR,MC,\$k,JC,V)

where:

	<u>Description</u>	<u>Type</u>
A	is the matrix whose inverse or determinant is to be determined. If simultaneous equations are to be solved the last MC - N columns of the matrix are the constant vectors of the equations to be solved. On output if the inverse is computed it is stored in the first N columns of A. If simultaneous equations are solved, the last MC - N columns contain the solution vectors.	floating-point array; input and output
NC	is the maximum number of columns of the array A.	FORTRAN integer; input
NR	is the maximum number of rows of the array A.	FORTRAN integer; input
N	is the number of rows of the array A.	FORTRAN integer; input
MC	is the number of columns of the array A. This entry is a dummy argument, if simultaneous equations are not solved.	FORTRAN integer; input

### A3.5 Subroutine GJR (Continued)

	<u>Description</u>	<u>Type</u>
k	is a statement number in the calling program to which control is returned if an overflow is detected. It must be preceded by \$ in the calling sequence	input
JC	is a one-dimensional permutation array of N elements used for permuting the rows and columns of A if an inverse is computed. If an inverse is not computed this argument must have at least one cell for the error return identification. On output, the first element of the array is N if control is returned normally. If an overflow is detected, the first element is the negative of the last correctly completed row of the reduction. If matrix singularity is detected, the entry contains the value of the last row before the singularity was detected.	FORTTRAN integer array; input and output
V	is a one-dimensional array. If the determinant is not computed it has one entry, otherwise it has two. On input V(1) is the option indicator, its values are set as follows:	floating-point array; input and output

	V(1)						
Operation	1.	2.	3.	4.	5.	6.	7.
Compute Determinant	no	yes	yes	no	no	yes	yes
Invert Matrix	yes	no	yes	no	yes	no	yes
Solve Equations	no	no	no	yes	yes	yes	yes

On normal return from the program V(1) contains the value of the natural logarithm of the absolute value of the determinant and V(2) contains the sign of the determinant. If an error return is made, and the determinant was to be computed, then V(1) is set to 0 and, if an overflow return was made, V(2) contains the sign of the last correct partially-computed value of the determinant.

### A3.5 Subroutine GJR (Continued)

Referenced by: INVERT

External References: None

Common Blocks: None

User Inputs: No ACPS options effect GJR. For modification see argument description above.

Printed Output: None

Special Considerations: If the matrix is singular or ill-conditioned, roundoff error may cause large discrepancies in the results.

In the case of a singular matrix, return may not be made through the singularity exit because of roundoff error.

Error Returns: If a singularity is detected, the first element of the array JC is set to the row number before the singularity was detected and, if the determinant was to be computed the value of V(1) is set to 0.0. Control is then returned to the calling program at the statement number specified.

If an overflow is detected, JC(1) is set to the negative of the last correctly completed row of the reduction. V(2) is set to the sign of the partial value of the determinant that was computed until this time. Control is then returned to the calling program at the statement number specified.

Mathematical Method: For any matrix A, if a matrix B exists such that  $BA = AB = I$  and I is the unit matrix, then  $B = A^{-1}$ .

If  $AX = C$ , where A is n by n, X is n by p, and C is n by p, then the solution to these sets of simultaneous equations is

$$X = A^{-1}C$$

### A3.5 Subroutine GJR (Continued)

The determinant of A is defined by the following equation

$$|A| = \sum (-1)^{f(j_1, \dots, j_n)} \prod_{i=1}^n a_{ij_i}$$

where:

$a_{ij}$  is the (i,j)th element of the matrix A.

$f(j_1, \dots, j_n)$  is the number of transpositions required to transform  $(1, \dots, n)$  to  $(j_1, \dots, j_n)$ ; the summation is over all permutations  $(j_1, \dots, j_n)$  of the integers  $(1, \dots, n)$ .

The solution to all of these problems is found by using a Gauss-Jordan elimination scheme with row scaling and maximal pivoting by columns.

Programming Method: For each column below the diagonal, the program searches for a pivotal element by finding the element of maximum absolute in the remaining rows of the column.

This row is interchanged with the row of the diagonal.

Each of the elements of the pivotal row is divided by the pivot except the pivot which is replaced by its reciprocal.

All the other rows of the array are changed by the formula

$$a_{ij} = a_{ij} - a_{ik}a_{kj}$$

where  $a_{kk}$  is the pivotal element. If  $i = k$ ,  $a_{ij}$  is replaced by 0.

When this process has been completed for each diagonal of the array, the columns of the matrix are repermuted to give the inverse in the first N columns of the array A.

### A3.5 Subroutine GJR (Continued)

If the determinant is to be found, each permutation of rows and columns changes the value of its sign. The natural logarithm of the absolute value of the diagonal element is summed after the second step.

Only the computations necessary for the options specified are carried out.



### A3.6 Subroutine INVERT

Description: INVERT provides an interface between NLSOLV and GJR. Any error condition indicated by GJR is displayed from here.

Usage: CALL INVERT(N,P,AA)

Referenced by: NLSOLV

External References: GJR

Common Blocks: None

User Inputs: None

Printed Output: 1) Inverse of the input partial derivative matrix  
2) Error message "\* \* ERRØR GJR" with values

### A3.7 Subroutine NLSOLV

Description: NLSOLV is the non-linear equation solver used by the ACPS program to find the values of the state vector which satisfy the constraint requirements. A complete discussion of the methods appears in Section 3.5.

Usage: CALL NLSOLV(N,X,XR,P,ZNORM,MAXIT,EPSTDY,EPSZ,Y,DYLIM,DYUP,YBNDL,  
YBNDU,NEWPAR)

Referenced by: SSPIPE

External References: GATHER, PARTAL, INVERT, FNORM

Common Blocks: None

User Inputs: X (state variable initial values), XR(XREF), MAXIT, EPSTDY,  
EPSZ,DYLIM,DYUP,YBNDL,YBNDU

Printed Output: 1) "NLSOLV ITERATION," (value), "FNORM =" (value)  
2) "MAXIMUM ITERATIONS"  
3) "NON-LINEAR SOLUTION IT = "(value)," FNORM =" (value)  
followed by the convergence summary

### A3.8 Subroutine PARTIAL

Description: This subroutine generates all of the partial derivatives  $(\partial f_i / \partial Y_j)$  for use in NLSOLV. An initial call to GATHER generates a reference state point. Successive calls in which each element of the state vector is independently varied by +2 percent produce corresponding constraint vectors from which the partial derivative matrix P is developed. See Section 3.5 for additional details of the procedure. The entire P-matrix is generated under  $\text{MODE} = 0$ . For the purpose of maintaining the accuracy of the P-matrix as the state vector is refined, the PARTIAL subroutine may be entered under  $\text{MODE} = K$  ( $K \neq 0$ ) in which case the K-th column of the P-matrix will be re-computed by perturbing the K-th element of the state vector.

Usage: CALL PARTIAL (N,Y,Z,P,YM,MODE,XR)

Referenced by: NLSOLV

External References: FNORM, GATHER

Common Block: None

User Inputs: None

Printed Output: "PARTIAL DERIVATIVE MATRIX" followed by the P-matrix. The columns correspond sequentially to the state variables as defined in the input array STATE, while the rows correspond sequentially to the constraint variables in order of imposition (see FCONCT).

After updating of P-matrix, the elements of the updated column are listed row-wise following the message "PARTIAL" (column number).

#### A4.0 Component Module Subroutines

This simulation program is structured in a general manner, with the specific capabilities depending primarily upon the component simulation modules available. The present version contains ten component modules tailored primarily for simulations related to spacecraft attitude control propulsion systems. However, sufficient capability and flexibility exists in these modules to permit convenient application to fluid systems in other fields, such as hydraulics and gas transfer. As other component modules become available, they may be added easily to the system within the present framework.

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#### A4.1 Subroutine ADIAB

Description: ADIAB is a subroutine which evaluates the frictional effects on a gas being transported through a thermally insulated (adiabatic) circular pipe or duct (see Section 4.1). The friction factor correlation employed assumes a hydraulically smooth wall surface. The gas was assumed ideal with constant properties as evaluated at the inlet conditions. The adiabatic line is one of four possible types (see A4.9) and is referenced by the LINE module by designating LTYPE(n) = 2 where n refers to the line identification number. As many as 70 lines are permitted so that  $1 \leq n \leq 70$ . The outlet pressure and/or pressure drop can be constrained.

Usage: CALL ADIAB(n)

Referenced by: LINE

External References: FCOMP3, PROP

Common Blocks: INDATA, CONS

User Inputs: IILINE, XLENGL, DIALI, PLØS, WDØT, PGI, TEMP1, PGPBL, DPLINE

Printed Output:

ADIABATIC LINE NUMBER	Line identification (II)
WDOT	Flow rate (lbm/sec)
PROPERTIES	Fluid number (NPLINE)
CP(II)	Fluid specific heat (B/lbm-°R)
KA	Specific heat ratio, $\gamma$ (-)
XLENGL	Line length (in)
DIALI	Line inside diameter (in)
IIRE	Reynolds number (-)
FRL	Total friction factor
PA	Inlet pressure (psi)
PGT1	Inlet total pressure (psi)
TA	Inlet temperature (°R)
TTEMP1	Inlet total temperature (°R)
MACH1	Inlet Mach number (-)
VEL	Average velocity (ft/sec)
RHO1	Fluid density (lbm/ft <sup>3</sup> )
PG2	Outlet pressure (psi)
PGT2	Outlet total pressure (psi)
TEMP2	Outlet temperature (°R)
TTEMP2	Outlet total temperature (°R)
MACH2	Outlet Mach number (-)
RHO2	Fluid density (lbm/ft <sup>3</sup> )

#### A4.2 Subroutine CHAM

Description: CHAM is the component module which simulates as many as ten liquid propellant combustion chambers. Fluid lines connected to the chamber (injector manifolds) are identified by LCHA1 and LCHA2. For bipropellant combustion chambers, the oxidizer and fuel sides may be interchanged. For a monopropellant combustion chamber, only the first injector is used. This module can be used to simulate both gas generators and thrusters depending upon whether or not a GG outlet line is specified (i.e., LCHAM(2) = 17). As a thruster, additional thrust-related calculations are performed and an automatic constraint is imposed requiring in effect that sonic conditions exist at the nozzle throat. When bipropellants are employed, a constraint is imposed requiring equality of the two injector outlet pressures. The user can specify, as required design conditions, the chamber pressure, mixture ratio, and either thrust or specific impulse, each one of which will cause an optional constraint to be imposed. Multiple design constraints must be used with special caution in conjunction with CHAM state variables so that the resulting problem is physically realistic and therefore mathematically well-posed.

Usage: CALL CHAM(IC)

Referenced by: GATHER

External References: VALVL, VALVG, FCONCT, CHMDAT, NEWRAP

Common Blocks: CONS, INDATA

User Inputs: Gas Generator

LCHA1, LCHA2, LCHAM, ARINJ1, ARINJ2, CDC1, CDC2, DISØC, PCD, CHAMMR

User Inputs: Thruster

Same as GG but delete LCHAM and add PATM, AREAT, ECSTAR, ECF, LAMDA, ERATIO, THRTD, ISPD.

## A4.2 Subroutine CHAM (Continued)

### Printed Output:

COMBUSTION CHAMBER NUMBER	ID number (1 to 10)
LINE 1	Line number - injector 1
LINE 2	Line number - injector 2
FLUID	Name of fluid
PC FLO	Injector outlet pressure (psi)
T LINE	Total temperature of inlet line ( $^{\circ}\text{R}$ )
W DOT	Mass flow rate (lbm/sec)
CD*A	Injector effective flow area ( $\text{in}^2$ )
MR	Mixture ratio (oxidizer/fuel)
P CHAM	Chamber pressure (psi)
T CHAM	Combustion temperature ( $^{\circ}\text{R}$ )
W NOZ	Nozzle flow rate (lbm/sec)
THRT	Thrust (lbf)
ISP	Specific impulse (lbf/lbm/sec)
CSTAR	$C^*$ (ft/sec)
C F	Thrust coefficient (-)
GAMMA	Specific heat ratio, $\gamma$
CP	Specific heat (B/lbm- $^{\circ}\text{R}$ )

#### A4.3 Subroutine CHOKe

Description: CHOKe is the component module used to impose the choked flow rate constraint at the outlet end of a pipe or duct. This constraint represents a physical boundary condition which typically applies at the end of a turbine exhaust duct. Provision for ten choked exit conditions are available. See Section 4.3.

Usage: CALL CHØKE(I)

Referenced by: GATHER

External References: FCONCT

Common Blocks: INDATA, CONS

User Inputs: LCHØKE, ACHØKE

Printed Output:

CHOKED EXIT  
LINE  
WCHØKE  
PRES T  
TEMP T  
GAMMA  
ACHØKE

ID number (I)  
Inlet line number  
Choking flow rate (lbm/sec)  
Line outlet total pressure (psi)  
Line outlet total temperature (°R)  
Specific heat ratio,  $\gamma$   
Exit flow area (in<sup>2</sup>)



#### A4.4 Subroutine FEEDB

Description: FEEDB is a lower-level subroutine called by the junction module to link the conditions at the beginning of a feedback loop with the conditions at the junction in the primary flow path from which the feedback loop branched. Two constraints are applied requiring equality of the corresponding total pressures and total temperatures. The junction module is instructed to call the feedback module by replacing the junction outlet line number with the feedback loop number (ten available) preceded by a negative sign. For example, LQJU1(2) = -3 indicates that the second outlet from junction number 1 is connected to feedback loop number 3.

Usage: CALL FEEDB (IF, PJ, TJ, WLINE)

Referenced by: JUNCL

External References: FCONCT

Common Blocks: INDATA

User Inputs: LFB, LØJU1, ... , LØJU10 = (negative values)

Printed Outputs: None

#### A4.5 Subroutine HEATEX

Description: HEATEX is the heat exchanger module described in Section 4.10.

A total of five heat exchangers are permitted. This is a lower-level routine which performs the nodal calculations in a step-wise manner from one end and which is controlled by the interface routine HEATX. For a counter-flow arrangement, HEATEX is executed iteratively to yield the proper inlet conditions.

Usage: CALL HEATEX (LN, LI, LØ, TI1, TØ1, TI2, TØ2, PI1, PØ1, PI2, PØ2, WDI, WDØ, QT, XI1, XØ1, TYPE)

Referenced by: HEATX

External References: PROPTY, SAT, LATENT, BPROPL, BPROGP, NUSLET, CWALL

Common Blocks: INDATA, HEAT

User Inputs: LENGTH, THICK, RI, RØ, HEWPA, HEWPB, ARFLA, ARFLB, DHYA, DHYB, HTAREA, FD, FN

Printed Output: None

#### A4.6 Subroutine HEATX

Description: HEATX is the interface module which controls execution of the heat exchanger subroutine. Five heat exchangers are permitted. HEATX calls HEATEX iteratively if the counter-flow type is specified. The user may optionally constrain the outlet temperatures by providing the desired values.

Usage: CALL HEATX (IH)

Referenced by: GATHER

External References: FCONCT, HEATEX

Common Blocks: INDATA, HEAT

User Inputs: LHXAI, LHXAØ, LHXB I, LHXBØ, HXRFLØ, HXCFLØ, THECA, THECB,  
XA, XB

Printed Output:

HEAT EXCHANGER	ID number
ITERATIONS	Counter-flow iterations to convergence
CONFIGURATION	(Names same as input)
LINE NO	Number of connected line
PRES A	Static pressure, side A (psi)
WDOT A	Flow rate, side A (lbm/sec)
TEMP A	Static temperature, side A (°R)

(side B same as side A)

PROPERTY DATA

DIST	Tube station (in)
PRES	Pressure (psi)
TEMP	Temperature (°R)
SP VOL	Specific volume (ft <sup>3</sup> /lbm)
QUAL	Quality (-)
NRE	Reynolds number (-)
NPR	Prandtl number (-)
CP	Specific heat, (B/lbm-°R)
COND	Thermal conductivity (B/in-sec-°R)
VISC	Fluid viscosity (lb/in-sec)

#### A4.6 Subroutine HEATX (Continued)

##### HEAT TRANSFER DATA

DIST	Tube station (in)
HE	Effective overall HT coefficient
HA	Side A HT coefficient (B/sec-in <sup>2</sup> -°R)
HW	Wall conductance (B/sec-in <sup>2</sup> -°R)
HB	Side B HT coefficient (B/sec-in <sup>2</sup> -°R)
T WALL A	Temperature, wall side A (°R)
T WALL B	Temperature, wall side B (°R)
K WALL	Wall thermal conductivity (B/sec-in)

#### A4.7 Subroutine ISOTH

Description: ISOTH is a subroutine which simulates the frictional effects on a gas being transported at a constant temperature (isothermally) through a circular pipe or duct (see Section 4.1). Constant gas properties and ideal gas equations are assumed. The friction factor is based on a correlation applicable to a hydraulically smooth wall. The isothermal line model is referenced by the LINE module by specifying LTYPE = 3. The total number of lines is 70. The user may require that the line pressure drop and/or line outlet pressure meet specified values (see LINE, Section A4.9).

Usage: CALL ISOTH (II)

Referenced by: LINE

External References: FCOMP2, PROP

Common Blocks: INDATA, CONS

User Inputs: NPLINE, XLENGL, DIALI, PLØS

Printed Output:

ISOTHERMAL LINE NO	Line ID number
WDOT	Mass flow rate (lbm/sec)
PROPERTIES	Fluid name
CP	Specific heat (B/lbm-°R)
VISC	Viscosity (lbm/ft-sec)
RGAS	Gas constant (ft-lbf/lbm-°R)
KA	Specific heat ratio, $\gamma$
XLENGL	Line length (in)
DIALI	Line inside diameter (in)
NRE	Reynolds number (-)
FRL	Friction factor
PG2	Outlet pressure (psi)
PGT2	Outlet total pressure (psi)
TEMP2	Outlet temperature (°R)
TTEMP2	Outlet total temperature (°R)
MACH2	Outlet Mach number (-)
RHO2	Outlet mass density (lbm/ft <sup>3</sup> )
PG1	Inlet pressure (psi)
PGT1	Inlet total pressure (psi)
TEMP1	Inlet temperature (°R)
TTEMP1	Inlet total temperature (°R)
MACH1	Inlet Mach number (-)
VEL1	Inlet velocity (ft/sec)
RHO1	Inlet density (lbm/ft <sup>3</sup> )

#### A4.8 Subroutine JUNCL

Description: JUNCL is the component module which simulates the physical conditions existing at a junction of three or more fluid lines. Storage has been provided for ten junctions, each of which can have one to five inlet lines and one to five outlet lines. If an outlet line begins a feed-back loop, the loop should be numbered (one through ten) and related to the junction through the FEEDB subroutine. If line 2 begins a feedback loop from the third outlet from junction 4, the connection would be specified as

$$LQJU4(3) = -1, \quad LFB(1) = 2.$$

An automatic constraint imposes a conservation of mass requirement on the solution. Also, if two or more lines merge at a junction, constraints are imposed to force equality of these line outlet pressures.

Usage: CALL JUNCL(I)

Referenced by: GATHER

External References: FEEDB, FCONCT

Common Blocks: INDATA

User Inputs: LIJU1, ... , LIJU10, LØJU1, ... , LØJU10

Printed Output:

JUNCTION NO.	Junction ID number
LINE	Connected Line ID number
WDOT	Flow rate in connected line (lbm/sec)
PRES T	Line total pressure (psi)
TEMP T	Line total temperature (°R)
PRES	Line static pressure (psi)
FEEDBACK LOOP NO.	ID number of feedback loop

#### A4.9 Subroutine LINE

Description: LINE is the basic component module by which all other component modules are interconnected. LINE also directs execution of ADIAB, ISOTH, and PIPL subroutines which simulate the effects of heat transfer and friction occurring in a circular pipe or duct. The basic module interconnections can be made with the "frictionless, adiabatic" line, which merely transfers data, by specifying LTYPE = 4. The other types of lines (see Section 4.1, A4.1, A4.7, and A4.10 for details) are selected by specifying LTYPE(n) = 2, LTYPE(n) = 3, or LTYPE(n) = 1, respectively. The outlet pressure of a line can be constrained to equal a user-specified constraint by using, for example, PGPBL(7) = 890. Similarly, the pressure drop in lines of type 1, 2, or 3 can be constrained as by DPLINE(8) = 10.

Usage: CALL LINE (II)

Referenced by: GATHER

External References: ADIAB, ISOTH, PIPL, FCONCT, PROP

Common Blocks: INDATA, CONS

User Inputs: LTYPE, NPLINE, DIALI, PGPBL, DPLINE, WDØT, PGI, PGT1, TEMPI, TTEMP1

Printed Output: (for types 1, 2, 3, see A4.10, A4.1 and A4.7, respectively)

FRICTIONLESS - ADIABATIC LINE	Line ID number
FLUID	Fluid number
W DOT	Mass flow rate (lbm/sec)
PRES	Static pressure (psi)
TEMP	Static temperature (°R)
PREST	Total pressure (psi)
TEMPT	Total temperature (°R)

#### A4.10 Subroutine PIPL

Description: PIPL is a detailed model considering the effects of both heat transfer and friction on the fluid being transported. This subroutine is referenced by LINE when LTYPE = 1. For gases, the pipe may be subdivided into as many as twenty sections, at the end of which the fluid properties are reevaluated. The friction factor is based upon correlations for hydraulically smooth pipes. Heat transfer by both radiation and natural convection is permitted. See Section 4.1 for computational details. As discussed in A4.9, the line outlet pressure and pressure drop may be constrained to specified values. The liquid state of a fluid is designated by a negative sign preceding the fluid type, NPLINE.

Usage: CALL PIPL (II)

Referenced by: LINE

External References: FCOMP1, PROP

Common Blocks: INDATA, CONS

User Inputs: NPLINE, XLENG, DIALI, TH, HR, WTHCON, ALPHA, PLØS, EMIS, GEE, TENV, KENV, VISE, NPRENV, RHOE, HNRE, HNPR, NODEL

Printed Output:

PIPL	Fluid type, name
LIQUID (GAS)	
LINE NO.	Line ID number
FLUID	Fluid ID number
NODES	Number of segments + 1
WDOT	Mass flow rate (lbm/sec)
LENGTH	Line length (in)
DIAM I	Inside diameter (in)
DIAM O	Outside diameter (in)
AREA I	Inside heat transfer area (in <sup>2</sup> )
RGAS	Gas constant (ft-lbf/lbm-°R)
CP	Specific heat (B/lbm-°R)
VISC	Fluid viscosity (lbm/ft-sec)
COND	Fluid thermal conductivity (B/ft-sec-°R)
NPR	Prandtl number (-)



#### A4.10 Subroutine PIPL (Continued)

KA	Specific heat ratio, $\gamma$
PRES	Static pressure (psi)
TEMP	Static temperature ( $^{\circ}\text{R}$ )
DENS	Fluid, density ( $\text{lbm}/\text{ft}^3$ )
MACH	Mach number (-)
VEL	Average cross sectional velocity (ft/sec)
NRE	Reynolds number (-)
NGR	Grashof number (-)
TWALL	Pipe wall temperature ( $^{\circ}\text{R}$ )
FRL	Friction factor
UAO	Overall thermal conductance
HRAD	Radiation H-T, coefficient
HO	Outside convection coefficient
HI	Inside convection coefficient
TOT P	Total pressure (psi)
TOT T	Total temperature ( $^{\circ}\text{R}$ )

#### A4.11 Subroutine PREG

Description: PREG is the component module which simulates the gross effects of a pressure regulator. The output pressure is no higher than the user input regulator pressure.

Usage: CALL PREG (I)

Referenced by: GATHER

External References: HPTH, OPTH

Common Blocks: INDATA, CONS

User Inputs: LPRI, LPRØ, PRE

Printed Output:

PA	Inlet pressure (psi)
PB	Outlet pressure (psi)
TA	Inlet temperature (°R)
TB	Outlet temperature (°R)
FUNC	Local iteration constraint
FUNCP	Local constraint derivative
RHO2	Fluid density (lbm/ft <sup>3</sup> )
WDOT	Mass flow rate (lbm/sec)
IPROP	Fluid ID number
ENTHA	Inlet enthalpy (B/lbm)
ENTHB	Outlet enthalpy (B/lbm)

#### A4.12 Subroutine PUMP

Description: Subroutine PUMP is the component module used to simulate the operation of a centrifugal pump. The pump performance is characterized by polynomial curves of pressure rise and required input power versus mass flow rate at the design speed. Evaluation of pump performance at off design speeds and scaling of pump for system sizing studies are accomplished through the use of similarity laws. A modeled system may contain five pumps. It is necessary to associate with each pump a corresponding turbine to provide definition of the pump speed and input power. The turbine module, however, need not actually be executed if the user specifies the turbine speed and power (either as constraints or as state variables with corresponding initial estimates). An automatic constraint equation is contained in the pump module to force equality of the input and required power. The user may specify a required pressure rise which will impose an optional constraint equation.

Usage: CALL PUMP (IP)

Referenced by: GATHER

External References: FCONCT

Common Blocks: INDATA, CONS

User Inputs: RPMT, P $\emptyset$ WT, ITURB, LPUMPI, LPUMP $\emptyset$ , RPM $\emptyset$ , DIAD, RDPUMP, GR, P $\emptyset$ WO, P $\emptyset$ W1, P $\emptyset$ W2, P $\emptyset$ W3, PW $\emptyset$ , PW1, PW2, DPPUMP

Printed Output:

PUMP	Pump number
DRIVEN BY TURBINE	Turbine number
LINE I	Number of inlet line
P IN	Inlet pressure, static (psi)
T IN	Inlet temperature ( $^{\circ}$ R)
RPM	Pump speed (RPM)
WDOT	Flow rate (lbm/sec)
LINE $\emptyset$	Number of outlet line
P OUT	Outlet pressure (psi)
T OUT	Outlet temperature ( $^{\circ}$ R)

#### A4.12 Subroutine PUMP (Continued)

POWER	Required power (ft-lbf/sec)
EPSLN	Power conversion efficiency
DENSITY	Fluid density (lbm/ft <sup>3</sup> )
CP	Fluid specific heat (B/lbm-°R)
GR	Turbine/Pump gear ratio
RDIA	Scaled/Design diameter ratio
RRPM	Actual/Design speed ratio

#### A4.13 Subroutine TANK

Description: Subroutine TANK is the module which simulates pressure vessels such as accumulators, surge tanks, gas bottles, and gas pressurized liquid propellant tanks. TANK is the only time dependent module used with this quasi-steady state simulation program. The storage conditions depend upon the initial conditions and the time integrals of the mass flow rates and heating rate. See Section 4.4 for a discussion of capabilities. The initial conditions of a tank are evaluated from user input at program TIME = 0. At each time point TIME + n DELT, n = 0, 1, ... , a quasi-steady system operating point is calculated. The solution vector is used as the initial estimate of the state vector for the succeeding time point. Time steps which yield successive operating points each in the vicinity of the preceding one, will produce the most rapid convergence. Automatic constraints are imposed as necessary to require equality of inlet line static pressures with the tank pressure.

Usage: CALL TANK (I)

Referenced by: GATHER

External References: PROP, BETA, INTEG, FCONCT

Common Blocks: INDATA, CONS, ARRAY

User Inputs: TIME, LDMI, LDMØ, LDWI, LDWØ, PTANK, TTANK, VTANK, TLIQ, WØL, PVENT, AVENT, CP1, CP2, R1, R2, DQIN

Printed Output:

** TANK NO.	Tank number
LGI	Number of inlet gas line
LGØ	Number of outlet gas line
LWI	Number of inlet liquid line
LWØ	Number of outlet liquid line
TIME	Program (simulation) time (sec)
P TANK	Tank pressure (psi)
T GAS	Gas temperature (°R)
T LIQ	Liquid temperature (°R)
W LIQ	Weight of liquid remaining (lbm)

#### A4.13 Subroutine TANK (Continued)

M1	Mass of gas species 1 (lbm)
M2	Mass of gas species 2 (lbm)
ALPHA	Mass ratio, $M1/(M1 + M2)$
ENERGY	Gas internal energy (B/lbm)
RHØ L	Liquid density (lbm/ft <sup>3</sup> )
DM1	Inlet flow rate, gas species 1 (lbm/sec)
DM2	Inlet flow rate, gas species 2 (lbm/sec)
DW NET	Inlet net liquid flow rate (lbm/sec)
DU	Rate of internal energy change (B/sec)
DQIN	Heating rate (B/sec)
CP1	Specific heat, species 1 (B/lbm-°R)
CP2	Specific heat, species 2 (B/lbm-°R)
RGAS 1	Gas constant, species 1 (ft-lb/lb-°R)
RGAS 2	Gas constant, species 2 (ft-lb/lb-°R)
V TANK	Tank volume (ft <sup>3</sup> )
DMVENT	Gas vent flow rate (lbm/sec)
PVENT	Valve vent pressure (psi)
AVENT	Vent valve flow area (in <sup>2</sup> )
1-PG/P	Deleted
1-PL/P	Deleted

#### A4.14 Subroutine TURB

Description: Subroutine TURB is the component module which simulates the operation of gas turbine (see Section 4.8). The turbine is characterized by the inlet effective choking area, rotor tip diameter, and an overall energy conversion efficiency which varies with the tip speed/isentropic spouting velocity ratio. This function is entered as a second order polynomial curve. Choking of the inlet flow is imposed by an automatic constraint. The back pressure at the turbine outlet is either PATM or a user-specified value PTURBØ (constraint or state variable). If a turbine duct is used, PTURBØ must be designated as a state variable. Some constraint downstream from the turbine (such as one occurring at a pressure boundary or a choked exit) must be associated with this state variable.

Usage: CALL TURB (IT)

Referenced by: GATHER

External References: FCONCT

Common Blocks: INDATA, CONS

User Inputs: LTURBI, LTURBØ, DIAT, AEFTUR, RPMT, CEF1, CEF2, PATM, PTURBØ

Printed Output:

TURBINE	Turbine number
LINE IN	Number of inlet line
LINE OUT	Number of outlet line
PT IN	Inlet total pressure (psi)
TT IN	Inlet total temperature (°R)
WDØT I	Inlet flow rate (lbm/sec)
CP TUR	Gas specific heat (B/lb-°R)
GAMMA	Specific heat ratio, $\gamma$
PT OUT	Turbine back pressure (psi)
TT OUT	Outlet temperature (°R)
W TUR	Turbine flow rate, choked (lbm/sec)
AEFTUR	Inlet choking area (in <sup>2</sup> )
DIAT	Rotor diameter (in)
POWT	Output shaft power (ft-lbf/sec)
ETA T	Overall efficiency
CEF1	Efficiency coefficient 1
CEF2	Efficiency coefficient 2
U/C	Speed ratio

#### A4.15 Subroutine VALVG

Description: VALVG is the component module which evaluates the pressure drop due to a perfect gas flowing subsonically through a valve, or orifice. The valve is characterized by the effective flow area, CDAV, which is the product of the flow coefficient and the physical flow area. The compressible orifice equation (Section 4.5), implicit in the downstream pressure, is evaluated iteratively. If a choking flow rate exists, the critical downstream pressure is used in default and an error message is printed. The user may optionally specify a required pressure drop across the valve in which case a constraint will be imposed. When the flow rate is negative, VALVG simulates a check valve, producing a pressure rise so that downstream constraints may be satisfied. The entry point CVALVG is used by the CHAM subroutine in computing the pressure drop across a combustion chamber injector.

Usage: CALL VALVG (I)

Referenced by: GATHER, (CHAM)

External References: NEWRAP, FCONCT

Common Blocks: INDATA, CONS

User Inputs: LVAI, LVAØ, CDAV, DPVALV

Printed Output:

VALVE CHOKED - FLOW RATE IN ERROR	Error message
VALVG - GAS VALVE NO.	Valve ID number
INLET LINE NO.	Number of inlet line
OUTLET LINE NO.	Number of outlet line
ITERATIONS	Number of calls to NEWRAP
P IN	Inlet pressure (psi)
P OUT	Outlet pressure (psi)
WDOT	Gas flow rate (lbm/sec)
CD*A	Effective flow area (in <sup>2</sup> )
R	Pressure ratio
FLOW RATE CHECKED	Check valve operation



#### A4.16 Subroutine VALVL

Description: VALVL is the component module which evaluates the pressure drop due to a liquid flowing through a valve or orifice. This valve is characterized by the effective flow area, CDAV, which is the product of the flow coefficient and the physical flow area. The incompressible orifice equation is used (Section 4.5). When the flow rate is negative, VALVL simulates a check valve, producing a pressure rise so that downstream constraints may be satisfied. The user may optionally specify the required pressure drop across the valve in which case a constraint will be imposed. The entry point CVALVL is used by the CHAM subroutine in computing the pressure drop across a combustion chamber injector.

Usage: CALL VALVL (I)

Referenced by: GATHER, (CHAM)

External References: FCONCT

Common Blocks: INDATA, CONS

User Inputs: LVAI, LVAØ, CDAV, DPVALV

Printed Output:

VALVG - GAS VALVE NO.	Valve ID number
INLET LINE NO.	Number of inlet line
OUTLET LINE NO.	Number of outlet line
W DOT	Liquid flow rate (lbm/sec)
PRES I	Inlet pressure (psi)
PRES Ø	Outlet pressure (psi)
TEMP	Liquid temperature (°R)
CD*A	Effective flow area (in <sup>2</sup> )

## A5.0 Supporting Subroutines

This section contains descriptions of lower level subroutines which support the component modules. Subroutine QQPCFW performs the tape writing function for the PREPRC program.

## A5.1 Function BETA

Description: The BETA function performs one-dimensional linear interpolation of data tables supplied through the calling arguments. Boundary points are returned for entries out of range. The points must be stored in increasing values of the independent variable, XTAB.

Usage: YOUT = BETA (YTAB, XTAB, XIN, NPPOINTS)

Referenced by: TANK, NUSLET, LATENT, BPROPG, BPROPL, H2OH2

External References: None

Common Blocks: None

User Inputs: None

Printed Output: None

## A5.2 Subroutine BINSER

Description: BINSER performs a binary search of an independent variable table for oxygen property interpolation routines.

Usage: CALL BINSER (T1, VB, 24, JJ, B)

Referenced by: THERM

External References: None

Common Blocks: None

User Input: None

Printed Output: None

### A5.3 Subroutine FCOMP1

Description: FCOMP1 performs an iterative calculation of the Mach number equation (Section 4.1, Equations 39-42) used in calculations for gas line with heat transfer and friction.

Usage: CALL FCOMP1 (X, MACHB, GF3)

Referenced: PIPL

External References: None

Common Blocks: None

User Inputs: None

Printed Output: "NO CONVERGENCE IN FCOMP1"

#### A5.4 Subroutine FCOMP2

Description: FCOMP2 performs iterative calculations of the pressure equation (Section 4.1, Equation 22) used in calculations of isothermal line module.

Usage: CALL FCOMP2 (X,PG2(II), GISØ)

Referenced by: ISOTH

External References: None

Common Blocks: None

User Input: None

Printed Output: "NO CONVERGENCE IN FCOMP2"

#### A5.5 Subroutine FCOMP3

Description: FCOMP3 performs iterative calculations of the outlet Mach number,  $M_o$  (Section 4.1, Equation 17), used in calculations of the adiabatic line module.

Usage: CALL FCOMP3 (W, MACH2, ADIA)

Referenced by: ADIAB

External References: None

Common Blocks: None

User Inputs: None

Printed Output: "NO CONVERGENCE IN FCOMP3"

#### A5.6 Subroutine INTEG

Description: INTEG performs numerical time integration by the trapezoidal rule of several variables appearing in the tank module. Initialization is performed when TIME = 0. The integrals are advanced when the value of the TIME variable exceeds the value stored during a previous call to this routine. If the time is not advanced from one call to the next (as occurs during the iterative loop), the integrals are recomputed but not advanced.

Usage: CALL INTEG (1, DM1, M1, TIME)

Referenced by: TANK

External References: None

Common Block: ARRAY

User Input: None

Printed Output: None



## A5.7 Subroutine INTER2

Description: INTER2 performs a two-dimensional linear interpolation of a general function Z of two independent variables, X and Y. If one or both input values lie outside the table ranges, the boundary value is returned.

Usage: CALL INTER2 (X, XTAB, Y, YTAB, Z, ZTAB, N, M)

Referenced by: H2OH2, NUSLET

External References: None

Common Blocks: None

User Input: None

Printed Output: None

## A5.8 Subroutine NEWRAP

Description: NEWRAP is a generalized Newton-Raphson iterator used to replace the loop coding and convergence testing employed for the iterative evaluation of an implicit function. Upon convergence or maximum (twenty) iterations, a normal return to the subsequent statement is made. During convergence, execution is returned to a user-defined statement number preceding the call.

Usage: (solve for root of  $F(R)$ )

```
      N = 1
      R = .8                      (initial estimate)
20  FR = F(R)                    (function to be zeroed)
      DFDR = FDERIV(R)           (derivative of F)
      CALL NEWRAP (R, FR, DFDR, N, 2, $20)
```

Referenced by: VALVG, CHAM

External References: None

Common Blocks: None

User Input: None

Printed Output: "\*\*\*\* NON-CONVERGENCE AT LOC," (number), (internal values)

## A5.9 Subroutine QQPCFW

Description: QQPCFW is a machine-dependent program written in assembly language which enables the user to write card images into the Program Complex File (PCF) area. Here, QQPCFW is used generating the dynamic subroutine GATHER.

Usage: CALL QQPCFW (IUNIT, IØP, NAME, IMAGE)

where:

IUNIT is physical unit of PCF tape

IØP is option flag

1 - Write from 14 word card image

2 - Write from 84 word card image

3 - Rewind tape

4 - Rewind tape and interlock

5 - Write end of file

NAME is name of current element

IMAGE is input card image

Referenced by: PREPRC

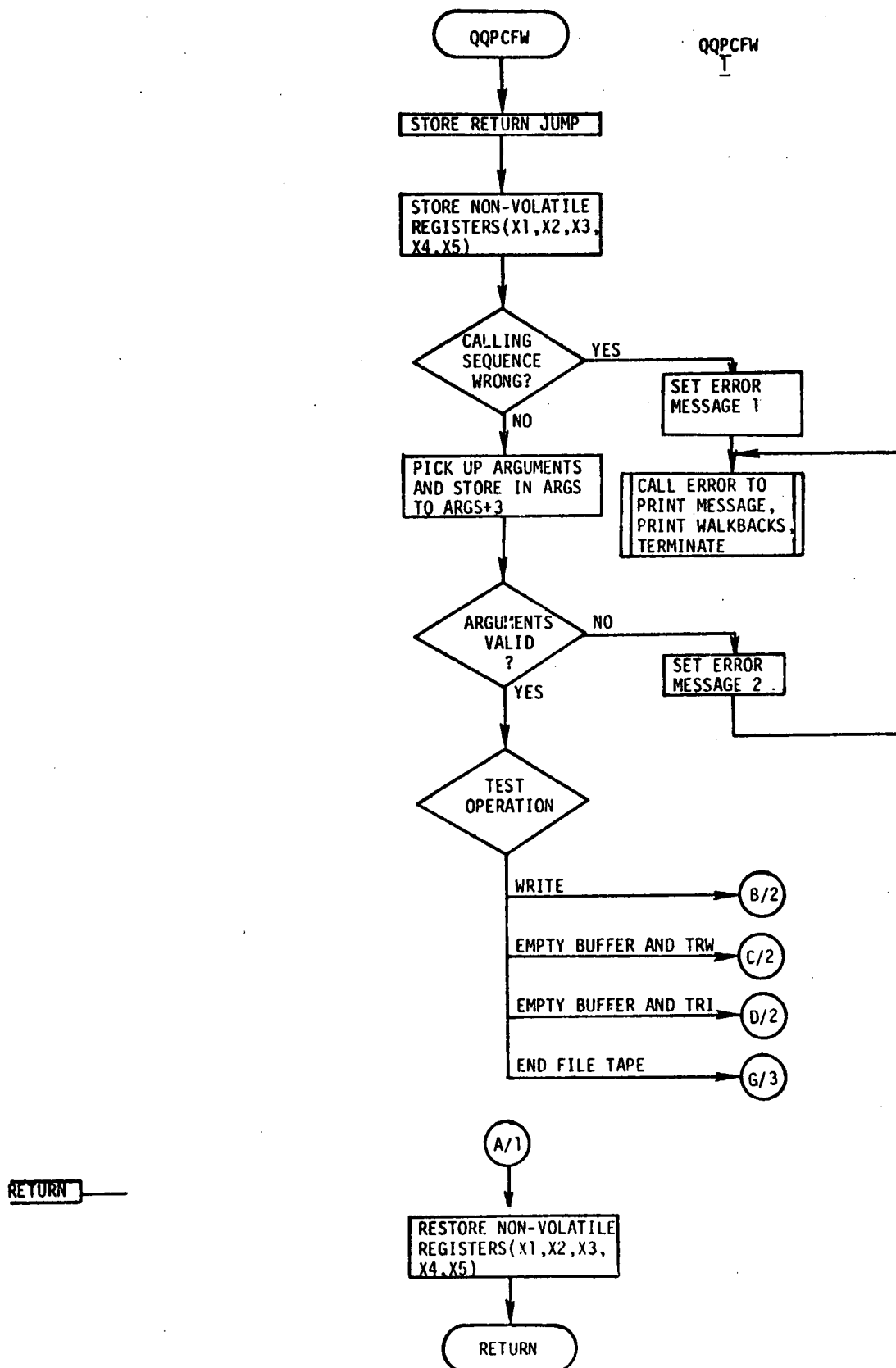
External References: None

Common Blocks: None

User Inputs: See above. No ACPS input options

Printed Output: None

Flow Chart: Since a Fortran listing is not available, the operation of QQPCFW is described by flow chart on the next eight pages.

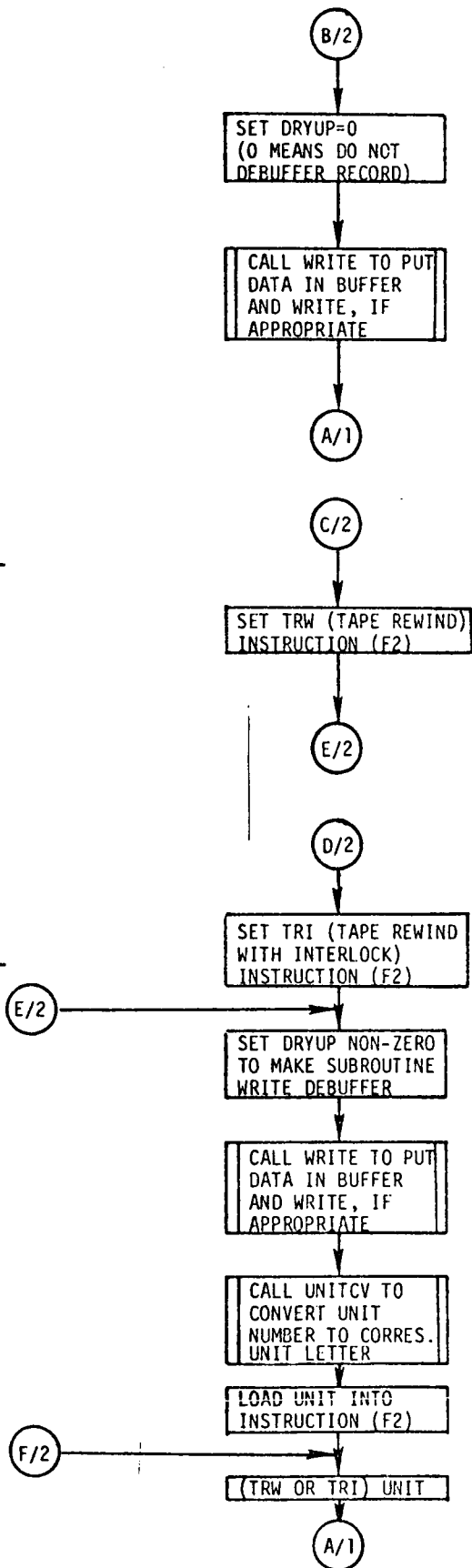


QQPCFW  
2

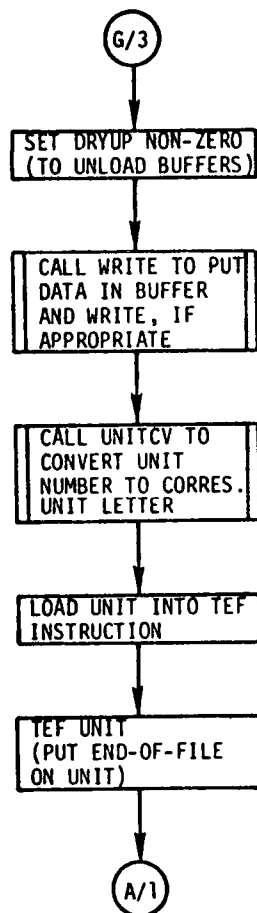
WRITE

EMPTY BUFFER  
AND TRW

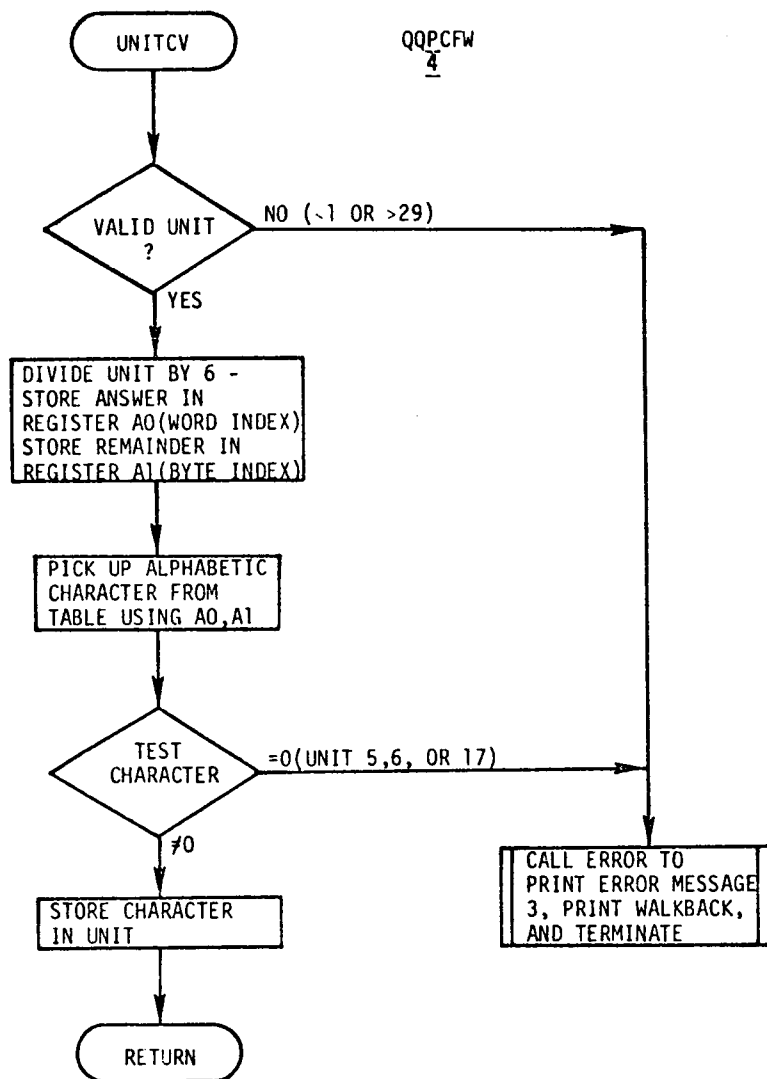
EMPTY BUFFER  
AND TRI



END FILE TAPE



QQPCFW  
3

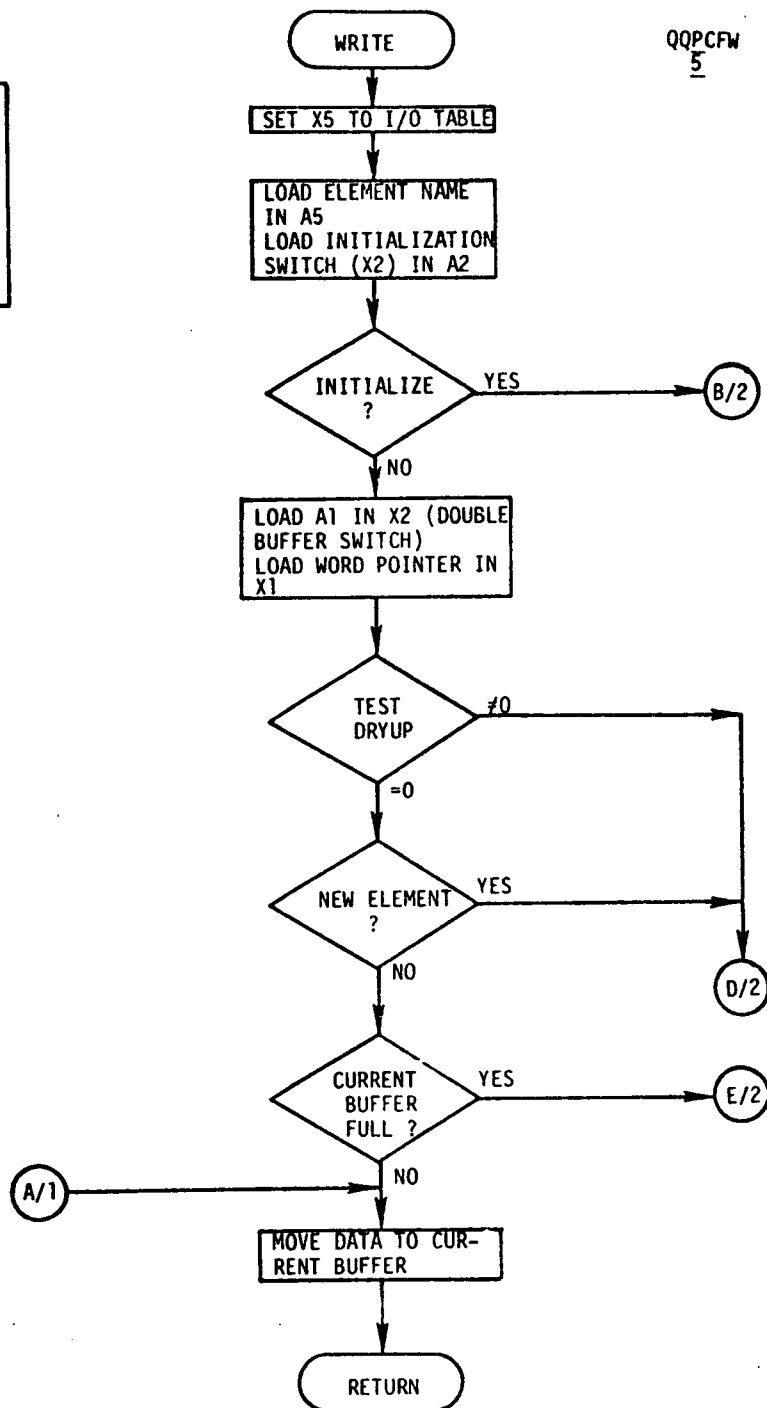


DATA RECORDS ARE  
DOUBLE-BUFFERED

SMALLEST RECORD  
THAT CAN BE WRITTEN  
IS 22 WORDS

DRYUP IS AN INPUT  
FLAG

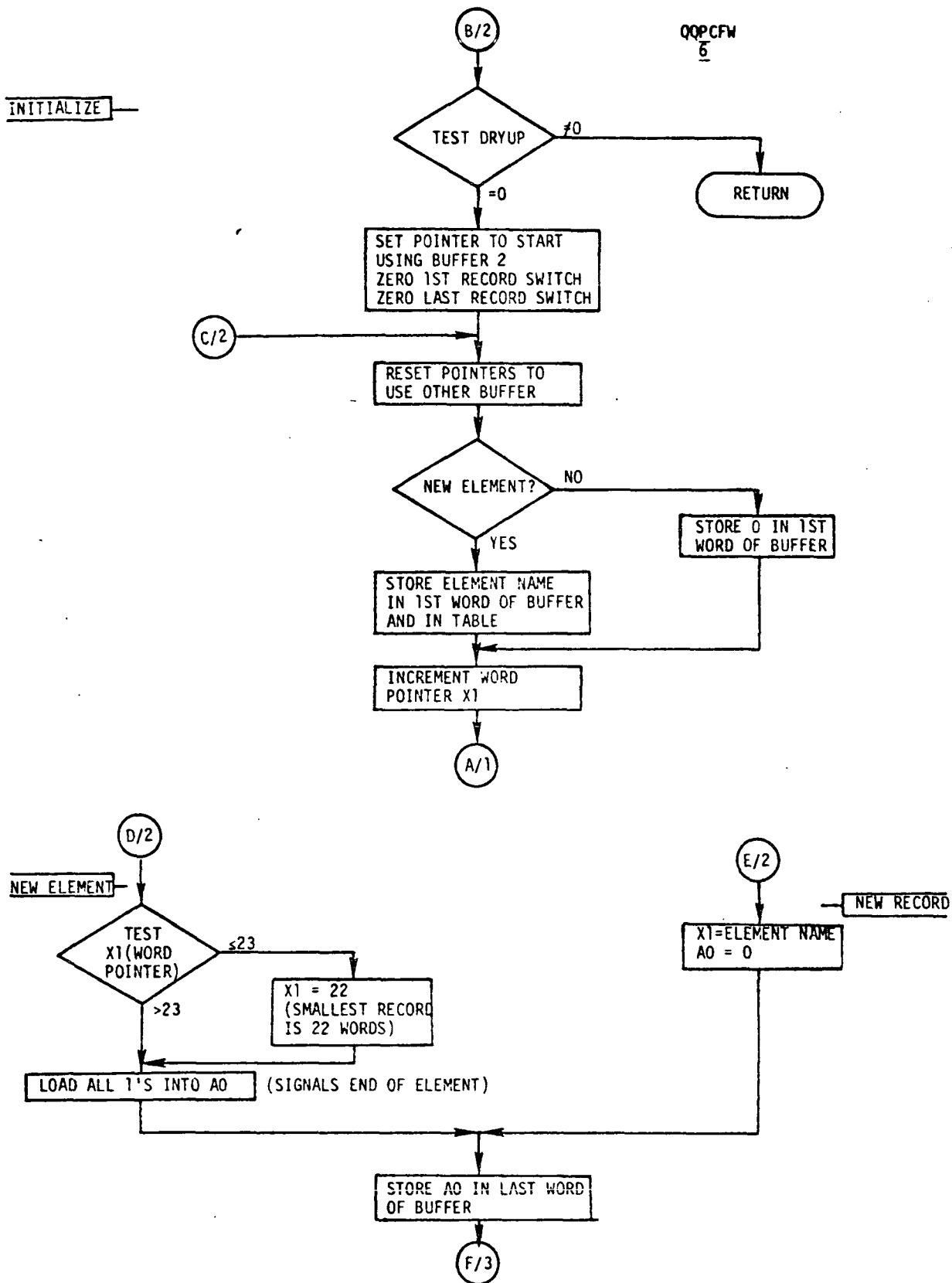
QQPCFW  
5

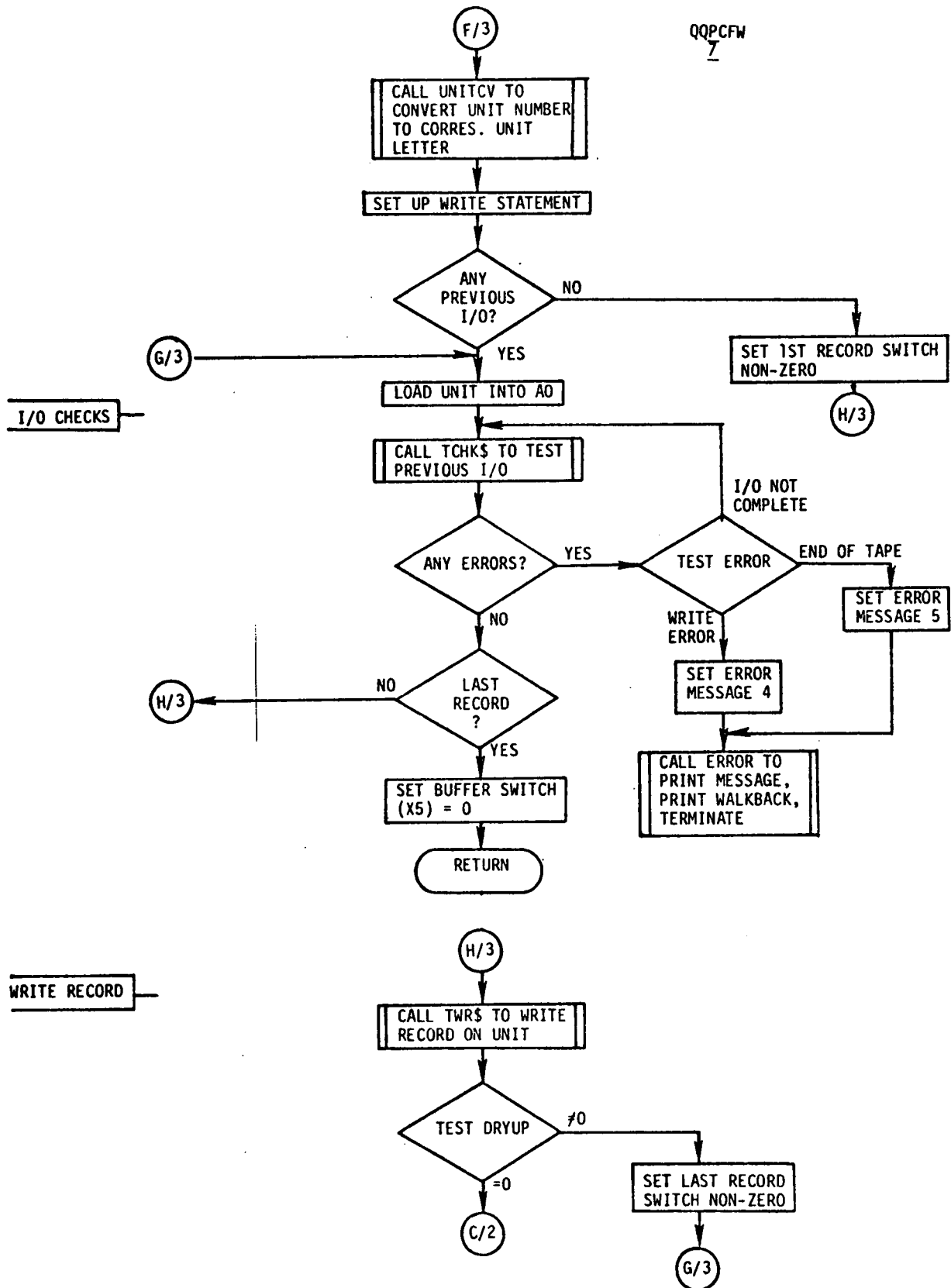




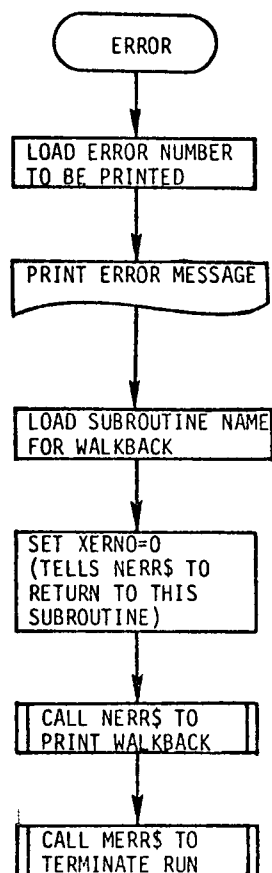
INITIALIZE

QOPCFW  
6





QQPCFW  
8



POSSIBLE ERROR MESSAGES:  
1-ILLEGAL NUMBER OF ARGUMENTS TO QQPCFW  
2-INCORRECT IOPERN ARGUMENT SUPPLIED QQPCFW  
3-INAPPROPRIATE UNIT  
4-WRITE ERROR OCCURRED - PROBABLY HARDWARE  
5-END OF TAPE ENCOUNTERED ON WRITE - JOB ABORTED

## A6.0 Input Processor

In order to provide the program user with a convenient means of loading card input data, an input processor called TRWLOD is employed, which accepts both numeric and alphanumeric data in free field format. Subroutines described in this section pertain to this input processor.

## A6.1 Subroutine BCDINT

Description: BCDINT converts a BCD number contained in array NCOL, one hollerith character per word, to the corresponding integer, INT. BCDINT first calls SQZB to adjust the non-blank words of NCOL to the front, in effect removing blanks from the hollerith number. Each word of NCOL is compared to the hollerith equivalent of the digits 0 through 9. When a match is found, the digit is packed into the integer, INT.

Usage: CALL BCDINT (NCOL, INT, N)

where:

NCOL is array containing input BCD number, one character per word.

INT is the integer corresponding to BCD characters in NCOL.

N is number of words in NCOL.

Referenced by: CDDATA

External References: SQZB

Common Blocks: None

User Inputs: No ACPs program options

Printed Output: None

## A6.2 Subroutine CDDATA

Description: CDDATA is called by TRWLOD for each input record. The record is read and resolved into the various fields, variable names, subscripts, control information, and individual data items. These fields are examined and categorized and loaded into a buffer (KRBF) with identifier for use by TRWLOD. Numerous error checks are performed as the record is processed.

Usage: CALL CDDATA

Referenced by: TRWLOD

External References: BCDINT, SQZB, PACK

Common Blocks: STAB, blank containing KRBF

User Inputs: No ACPS program options

Printed Output: Error message

"ILLEGAL USE OF CHARACTER ( ) IN OR AFTER COLUMN ( )."

Record Format: The records acceptable to CDDATA are free form in that the information may be in columns 1-72. Columns 73-80 may be used for sequencing or for miscellaneous information which is only read in and printed out on the user specified output unit.

All columns between two separators comprise a field. A separator may be an equal sign, a comma, an asterisk, a slash, a parenthesis, an R preceded by an integer, or apostrophes enclosing BCD characters. Blanks are permissible within all fields. An asterisk (\*) except after an apostrophe for enclosing BCD characters terminates the scan, and speeds processing of the record.

Data information may be continued from one record to the next record by omitting the symbol name with storage of the information continuing in the next consecutive cell. Data may be input for any location of a dimensioned variable (one-, two-, or three-dimensional array) by designating

## A6.2 Subroutine CDDATA (Continued)

the subscript in parenthesis for a single dimensioned array ( $A = (3), 10.0$ ), by designating the number of rows between slashes followed by the subscript for a two-dimensional array ( $B = /3/(3,3), 10.9$ ), or by designating the number of rows and columns between slashes followed by the subscript for a three-dimensional array ( $C = /3,2/ (2,2,3), 9.99$ ). A three-dimensional array is the largest accepted by subroutine CDDATA.

A BCD word preceding an equal sign (=) is a symbol, and all succeeding information is considered data for this symbol until the next symbol is encountered. Octal integers are input as  $\emptyset 123456700000$ , where the number must be preceded by the letter  $\emptyset$  and is stored from left to right as read.

The values of all symbols are stored in the buffer in the same format in which they appear in the record, i.e., BCD, integer, real, octal, or double precision. More than one symbol and its associated value(s) may appear in each record, i.e.,  $X = 3.0, B = (2), 3.2, I = 4^*$ .

### Error/Action Messages:

"ILLEGAL USE OF CHARACTER\_\_\_\_\_ IN OR AFTER COLUMN\_\_\_\_\_"

This message is written when an illegal character is located in any of the various fields. A few of the possible errors are as follows:

a digit larger than 7 in an octal number, two  
decimals in a real number, and a decimal in an  
exponent.

Restrictions: CDDATA will not store information in arrays having more than three dimensions.

## A6.2 Subroutine CDDATA (Continued)

Method: CDDATA reads a record using a 72A1, A6, A2 format, prints this record image if requested, and processes the various fields while storing the information in a buffer to be returned to Subroutine TRWLOD. CDDATA scans the record until a field separator is located according to the separation of the field contents. The field and group type flags are defined as follows:

<u>Field Type</u>	<u>Definition</u>
1	Symbol followed by an equal sign (6 characters or less)
2	Single precision word (real)
3	Single precision word (integer)
4	Double precision word
5	BCD string preceded by an apostrophe
6	BCD string not preceded by an apostrophe
7	Octal integer
<u>Group Type</u>	<u>Definition</u>
20	Dimension group
30	Subscript group
40	Repeat group

The group type will always contain a field type 3, i.e., 23, 33, or 43, representing a dimension, subscript, or repeat integer, respectively.

When the type flag has been determined and the field processed, the type flag followed by the processed field is stored in the buffer. The procedure is repeated for all fields in the record until reaching an asterisk (\*) or column 73, at which time a zero is stored in the next buffer cell signifying the end of the data. The number of buffer cells



## A6.2 Subroutine CDDATA (Continued)

used for this record is stored in the buffer cell 109. The buffer has a storage capacity of 108 cells.

Each symbol requires three buffer cells, one for the type flag, one for the field (symbol name), and one for the symbol storage address. Each double precision number uses three buffer cells, one for the type flag and two for the field (value). Each BCD field uses two buffer cells plus the number of buffer cells (six record columns per cell) needed for the field (BCD string); one for the type flag, one indicating the number of BCD words in the field, and the rest for the field. All the other fields only require two buffer cells, one for the type flag and one for the field.

When a symbol is located, the table KSYMB is searched for this symbol, and if found, the address corresponding to the symbol is extracted from the table and stored in the buffer. If this symbol does not exist in the table KSYMB, it is an illegal input signified by a zero in the storage address cell of the buffer for this symbol.

### Examples

Data record Y = /5/ (1,2) 29.4, (2,3) 100.9, 1.2, 7.6\*

<u>Buffer</u>	<u>Definition</u>
KRBF(1) = 1	Type (symbol)
= Y	Field (symbol name)
= _____	Address of symbol
= 23	Type (dimension integer)
= 5	Field (number of rows)
= 33	Type (subscript integer)
= 1	Field (row subscript)
= 33	Type (subscript integer)

## A6.2 Subroutine CDDATA (Continued)

<u>Buffer</u>	<u>Definition</u>
= 2	Field (column subscript)
= 2	Type (real)
= 29.4	Field (value of Y(1,2))
= 33	Type (subscript integer)
= 2	Field (row subscript)
= 33	Type (subscript integer)
= 3	Field (column subscript)
= 2	Type (real)
= 100.9	Field (value of Y(2,3))
= 2	Type (real)
= 1.2	Field (value of Y(3,3))
= 2	Type (real)
KRBF(21) = 7.6	Field (value of Y(4,3))
KRBF(22) = 0	Type (end of record)
⋮	
KRBF(109) = 22	Number of buffer cells used for this record

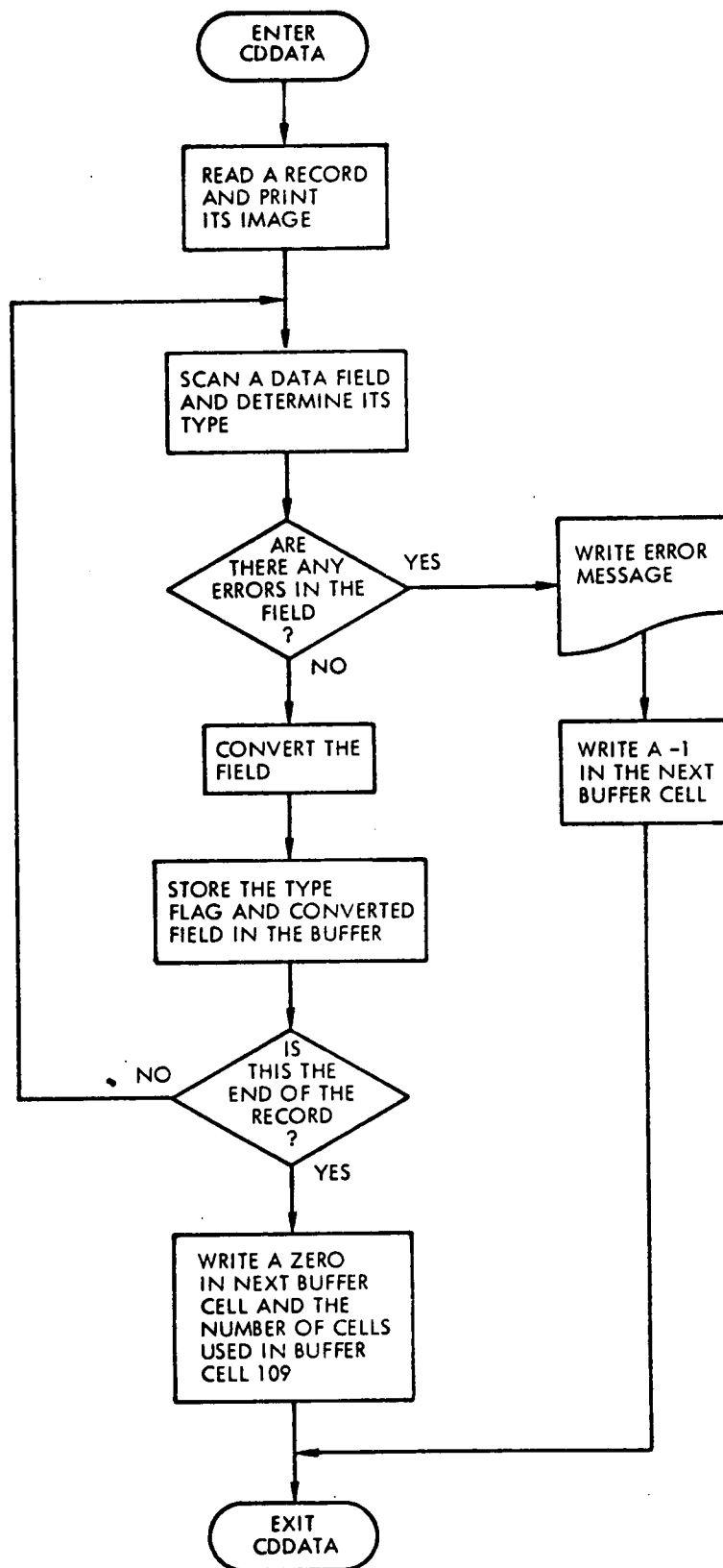
Data record X = 123., THIS IS NOT A SYMBOL, 012, 1D5\*

<u>Buffer</u>	<u>Definition</u>
KRBF(1) = 1	Type (symbol)
= X	Field (symbol name)
= _____	Address of symbol
= 2	Type (real)
= 123.	Field (value of X(1))
= 6	Type (BCD string not preceded by an apostrophe)

## A6.2 Subroutine CDDATA (Continued)

<u>Buffer</u>	<u>Definition</u>
= 4	Field (number of BCD words)
= THIS I	Field (value of X(2))
= S NOT	Field (value of X(3))
= A SYMB	Field (value of X(4))
= 0L	Field (value of X(5))
= 7	Type (octal)
= 120000000000 <sub>8</sub>	Field (value of X(6))
= 4	Type (double precision)
= }	Field }
= }	Field } (value of X(7) and X(7)+1)
KRBF(17) = 0	Type (end of record)
⋮	
KRBF(109) = 17	Number of buffer cells used for this record

A functional flow chart of this subroutine is shown on the next page.



FLOW CHART CDDATA

### A6.3 Function DP2R

Description: DP2R converts a double precision number to single precision.

Usage:  $Y = \text{DP2R}(X)$

where X is double precision real.

Referenced by: TRWLOD

External References: None

Common Blocks: None

User Input: None

Printed Output: None

#### A6.4 Subroutine PACK

Description: This subroutine packs BCD characters (one character per word) into an array of six BCD characters per word.

Usage: CALL PACK (NCARD, LWØRD, N)

where:

NCARD is an input array in which all words have one left-justified BCD character.

LWØRD is the output array containing six BCD characters per word

N is the number of words in NCARD on input or in LWØRD on output

Referenced by: CDDATA

External References: None

Common Blocks: None

User Inputs: No ACPS program options

Printed Output: None

Method: PACK moves and combines BCD characters using bit manipulation and logical functions. The technique used to perform this function in the routine allows the subroutine to remain compatible for use on both the UNIVAC 1108 and the IBM 7094 computers. The following example shows a typical use of PACK: let NCARD be the eight word array (one left-justified BCD character per word) "EXAMPLES" (i.e., NCARD = Ebbbbbb, Xbbbbbb, etc.), on output, LWØRD(1) = EXAMPL and LWØRD(2) = ESbbbb. N should be input equal to 8, and it will be returned equal to 2. NCARD is not restricted to alphabetic characters but may contain any alphanumeric characters.

## A6.5 Function R2DP

Description: R2DP converts a real single precision number to double precision.

Usage:  $X = R2DP(Y)$

where Y is single precision

Referenced by: TRWLOD

External References: None

Common Blocks: None

User Input: No ACPS program options

Printed Output: None

## A6.6 Subroutine SQZB

Description: The input language or numerical input may in certain places contain blanks which must be removed prior to processing. SQZB is called for this purpose.

Usage: CALL SQZB (NCØL, N)

where:

NCØL is an array of BCD characters, one character per word. The words are rearranged placing the non-blank words toward the beginning.

N is the number of words in NCØL. On output, N is the number of non-blank words.

Referenced by: CDDATA

External References: None

Common Blocks: None

User Input: No ACPS program options

Printed Output: None

Method: SQZB removes blanks from unpacked (one character per word) arrays of variable length. Non-blank words are left-justified in the array and the remaining words are blanked.

### Example:

Let the input array NCØL be ten words long with each word containing one BCD character (left-justified with blank fill): b, b, S, A, M, b, P, L, b, E (where "b" represents a blank). On return from SQZB the array NCØL will be: S, A, M, P, L, E, b, b, b, b, one character per word, with N=6.



#### A6.7 BLOCK DATA TRWDAT

Description: TRWDAT contains a table equating the octal addresses in the S-array (common block INDATA) with the input variables names to be recognized by the input processor TRWLOD.

Usage: Data loaded by system

Referenced by: TRWLOD, CDDATA

External References: None

Common Blocks: STAB

User Input: None

Printed Output: None

## A6.8 Subroutine TRWLOD

Description: TRWLOD is a data input processor which transfers data stored in a buffer (KRBF) to the locations in a named common block (here INDATA) specified by data in TRWDAT.

Usage: CALL TRWLOD (IIN, IØUT, K)

where:

IIN is input BCD tape unit,

IØUT is output unit for record images, and

K is an error flag.

Referenced by: PREPRC, SSPIPE

External References: CDDATA, DP2R, R2DP, TRWDAT

Common Blocks: STAB, INDATA, blank

User Inputs: No ACPS program options

Printed Output: Error messages, see below.

Error/Action Messages:

- 1) "ERROR IN SUBSCRIPT (SEE BUFFER WORD \_\_\_\_)"

This error message is written for any of the following subscript errors. The type flag from the buffer designates that a dimension integer is specified when the dimension has already been defined, the column subscript is being used without the number of rows having been specified, or the third subscript is being used without the number of columns being specified.

- 2) "INCORRECT DATA TYPE. NO CONVERSION POSSIBLE.

\_\_\_\_ WAS EXPECTED, \_\_\_\_ FOUND ON CARD (SEE BUFFER WORD \_\_\_\_.)"

This message is written when the type of the given value is not

#### A6.8 Subroutine TRWLOD (Continued)

consistent with the specifications in bits 18-20 of the address word NADR and the value cannot be converted without changing its value.

3) "\_\_\_\_ IS AN ILLEGAL SYMBOL"

This message is written when the variable name in the buffer is not a legal symbol.

4) "ILLEGAL DATA CARD CONTAINED IN BUFFER"

This message is written when the type flag is greater than 7, a symbol has not been defined ( $J=0$ ) and the first buffer cell contains a value other than a 1; i.e., the first data card is a continuation card, or when non-integer subscript, dimension, or repetition values have been used.

5) "ERROR INVOLVING REPETITION OF DATA FIELD (SEE BUFFER WORD \_\_\_\_)"

This message is written when either a negative or zero number of repetitions have been requested or repetition of a non-repeatable field is indicated, i.e., symbol name, subscript, etc.

Method: TRWLOD calls Subroutine CDDATA to process a data record and returns the information contained by a buffer. TRWLOD processes this information storing the value(s) in the location(s) specified according to the given subscript(s) (if any). TRWLOD checks the type of the value in the buffer with the type specified for each variable, and if the types are not compatible, the value is converted providing the conversion can be accomplished without altering the values. For instance, integers will be converted to real numbers and real numbers converted to integers when conversion does not cause truncation of the fractional part.

#### A6.8 Subroutine TRWLOD (Continued)

If the type flag from the buffer designates that a symbol is in the next buffer location, the symbol is stored in the variable "NAME." The buffer cell (stored in "NADR") following the symbol has the storage address in bits 21-35 and the type (real, integer, BCD, octal, etc.) of the value(s) expected in bits 18-20 (stored in "LL"). If the storage address is zero and the symbol is not "ENDCAS," this is an illegal symbol, and error message number 3 is written. If the symbol was "ENDCAS," control is returned to the calling subroutine.

A type flag equal to a two, three, four, five, six, or seven (type real, integer, double precision, BCD chracters limited by apostrophes, BCD characters, or octal, respectively) designates the type of the value in the next buffer cell. If this type does not agree with "LL," the value is converted, if possible, without changing its value, e.g., integer to real; otherwise, error message number 2 is written. For any value being converted, the message "INPUT VALUE \_\_\_\_ CONVERTED TO \_\_\_\_" is written. If the type flag is the same as the value of "LL," "LL" is equal to zero, or if the value has been converted, the value is stored according to its subscripts (if any). A type flag equal to 1 causes error message number 4 to be written.

A type flag of 33 or 23 (type subscript integer or dimension integer, respectively) designates that a subscript or dimension information is contained in the next buffer cell. When receiving subscript or dimension information, the subscript or dimension is determined, and if not correctly specified, error message number 1 is written.

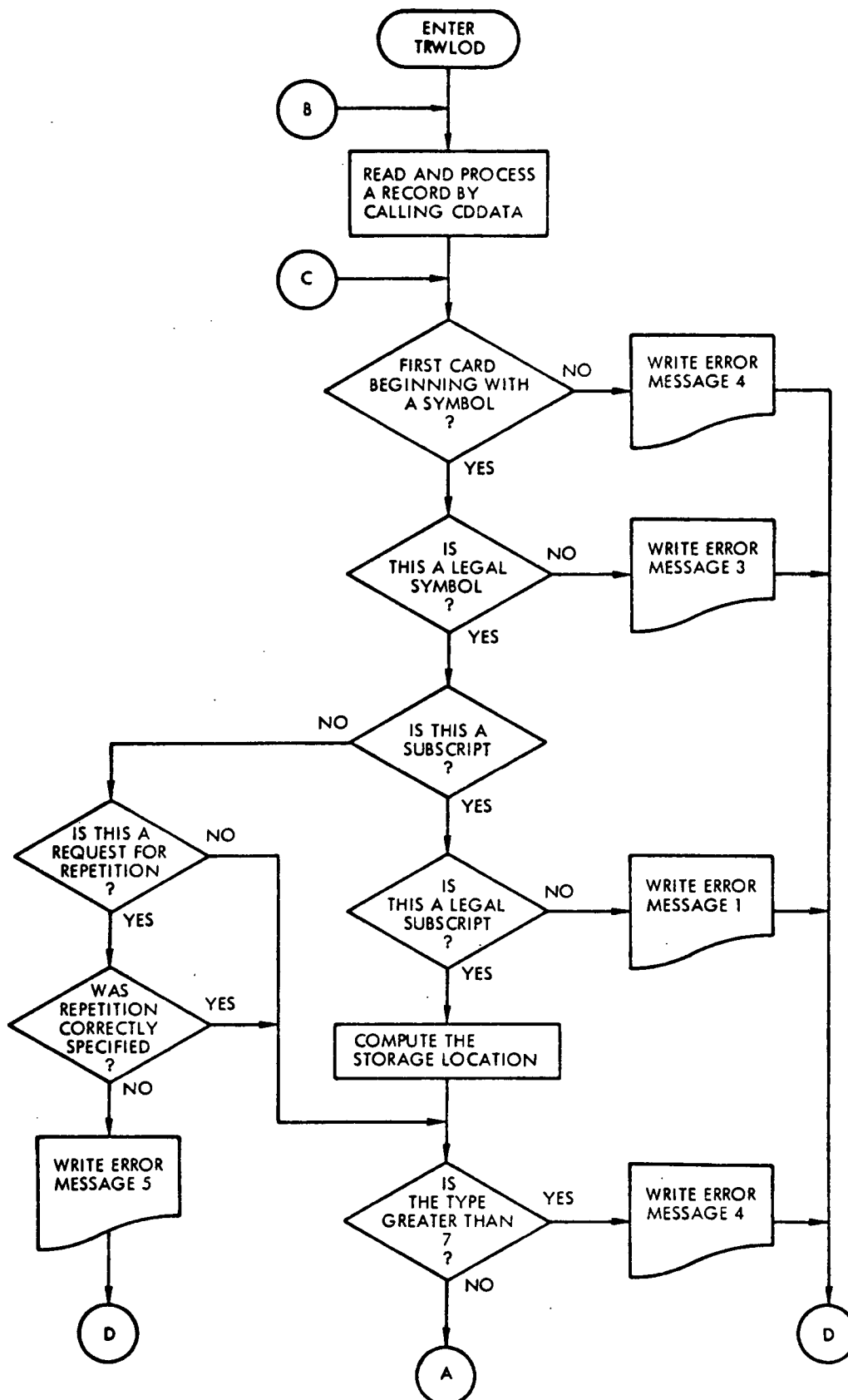
A type flag of 43 (repeat integer) signifies repetition of the following field is to take place the number of times specified in the next buffer location (location following the 43).

#### A6.8 Subroutine TRWLOD (Continued)

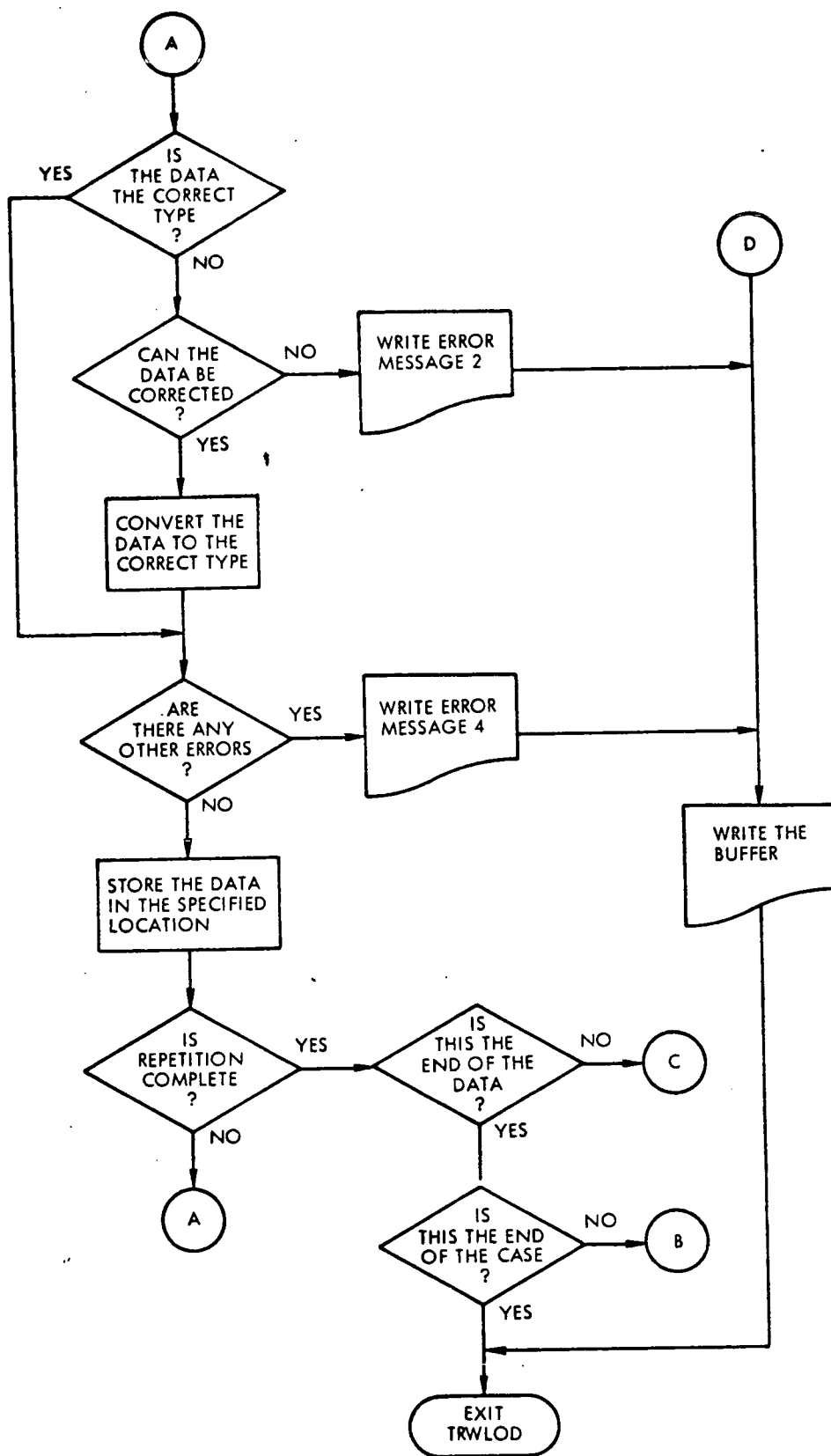
If "LL" is equal to zero, the values are stored as they are input without any conversion. A type flag equal to zero in the buffer indicates that all information in the buffer has been processed.

After any error message is written, the buffer is dumped for use in diagnosing the error.

A functional flow chart of this subroutine is shown on the next two pages.



FLOW CHART TRWLOD



FLOW CHART TRWLOD

## A7.0 Property Subroutines

This section contains descriptions of the many thermodynamic property data subroutines required to support the various component modules incorporated in the ACPS program.



#### A7.1 Data BLK1

Description: BLK1 contains hydrogen thermodynamic property data used in Subroutine HPTH.

Usage: Data loaded by system.

Referenced by: HPTH

External References: None

Common Blocks: BLKPTH

User Inputs: None

Printed Output: None

## A7.2 Data BLK2

Description: BLK2 contains hydrogen thermodynamic property data used in Subroutine PTHEAT.

Usage: Data loaded by system

Referenced by: PTHEAT

External References: None

Common Blocks: SPHEAT

User Inputs: None

Printed Output: None

### A7.3 Subroutine BPROPG

Description: This subroutine supplies thermodynamic property data for gaseous hydrogen or oxygen at saturation conditions. Used for boiling heat exchanger.

Usage: CALL BPRØPL (IFLUID, PX, TSAT, SV, MU, K, CP, PR)

Referenced by: HEATEX

External References: BETA, HPTCP, HPTV, HPTTC, OPTV, OPTTC

Common Blocks: None

User Inputs: None

Printed Output: None

#### A7.4 Subroutine BPROPL

Description: This subroutine supplies thermodynamic property data for liquid hydrogen or oxygen at saturation conditions. Used for boiling heat exchanger.

Usage: CALL BPROPL (IFLUID, PX, TSAT, SV, MU, K, CP, PR)

Referenced by: HEATEX

External References: BETA, HPTCP, HPTV, HPTTC, OPTV, OPTTC

Common Blocks: None

User Inputs: None

Printed Output: None

## A7.5 Subroutine CHMDAT

Description: CHMDAT is the combustion chamber characterization data routine. Data is provided for the propellant combinations hydrogen/oxygen, aerazine-50/nitrogen tetroxide, monomethylhydrozine/nitrogen tetroxide, and hydrozine monopropellant. The characterization consists of tabular functions of characteristic exhaust velocity ( $C^*$ ), combustion temperature, specific heat ratio, and specific heat ( $C_p$ ) versus the two independent parameters, combustion pressure and mixture ratio. Two-dimensional linear interpolation is employed. For hydrozine monopropellant, the mixture ratio is replaced by fraction  $\text{IH}_3$  dissociated.

Usage: CALL CHMDAT (NP1, NP2, RI, PI, CSTAR, TC, GAM, CP)

Referenced by: CHAM

External References: None

Common Blocks: None

User Inputs: None

Printed Output: "\*\*\* EXTRAPOLATION REQUIRED FOR COMBUSTION PROPERTIES  
(IC, MR,  $P_c$ )" \*\*\* ERROR - COMBUSTION PROPERTIES REQUESTED NOT AVAILABLE  
PROPELLANTS =" (propellant ID numbers)

#### A7.6 Subroutine CWALL

Description: CWALL computes the thermal conductivity of AISI 347 stainless steel.

Usage: CALL CWAL (T, K)

Referenced by: HEATEX

External References: None

Common Blocks: None

User Inputs: None

Printed Output: None

#### A7.7 Function HPTCP

Description: Name change for hydrogen specific heat ( $C_p$ ) call statement.

See Subroutine PTHEAT.

Usage: CP = HPTCP(P,T)

Referenced by: PROP

External Reference: PTHEAT

Common Blocks: None

User Inputs: None

Printed Output: None

#### A7.8 Function HPTCV

Description: Name change for hydrogen specific heat ( $C_v$ ) call statement.

See Subroutine PTHEAT

Usage:  $CV = HPTCV(P,T)$

Referenced by: PROP

External References: PTHEAT

Common Blocks: None

User Inputs: None

Printed Output: None



#### A7.9 Function HPTD

Description: HPID is the hydrogen density data routine covering the range  
P = 1 to 5000 psi, T = 24.16 to 5000 °R as obtained from National Bureau of  
Standards.

Usage: RHØ = HPTD(P,T)

Referenced by: PROP

External References: None

Common Blocks: None

User Inputs: None

Printed Output: None

#### A7.10 Function HPTH

Description: HPTH is the hydrogen enthalpy data routine covering the range  $P = 1$  to 5000 psi,  $T = 24.16$  to 5000 °R as obtained from National Bureau of Standards.

Usage:  $ENTH = HPTH(P,T)$

Referenced by: PROP, PREG

External References: None

Common Blocks: BKLPTH (BLOCK DATA BLK1)

User Input: None

Printed Output: None

#### A7.11 Function HPTTC

Description: HPTTC is the hydrogen thermal conductivity routine obtained from National Bureau of Standards.

Usage:  $K = \text{HPTTC}(P, T)$

Referenced by: PROP

External References: None

Common Blocks: None

User Input: None

Printed Output: None

#### A7.12 Function HPTV

Description: HPTV is the hydrogen viscosity routine obtained from National Bureau of Standards.

Usage: MU = HPTV(P,T)

Referenced by: PROP

External References: None

Common Blocks: None

User Input: None

Printed Output: None

### A7.13 Subroutine H2O<sub>2</sub>

Description: This routine computes the thermodynamic properties of the combustion products of hydrogen and oxygen at the assumed mixture ratio of 1.0.

Usage: CALL H2O<sub>2</sub> (P, T, SV, MU, K, CP, PR)

Referenced by: PROPTY

External References: BETA, INTER2

Common Blocks: None

User Inputs: None

Printed Output: None

#### A7.14 Subroutine LATENT

Description: LATENT provides the enthalpies of hydrogen or oxygen at the saturated liquid and saturated gas conditions by linear interpolation of enthalpy-pressure tables.

Usage: CALL LATENT (IFLUID, PX, ENTHL, ENTHG)

Referenced by: HEATEX

External References: BETA

Common Blocks: None

User Inputs: None

Printed Outputs: None

#### A7.15 Subroutine NUSLET

Description: NUSLET evaluates the Nusselt number correlation equations for hydrogen, oxygen, or their combustion products flowing through a heat exchanger.

Usage: CALL NUSLET (N, PR, RE, TW, TB, MART, NU)

Referenced by: HEATEX

External References: BETA, INTER2

Common Blocks: HEAT (link with heat exchanger)

User Inputs: None

Printed Output: None

#### A7.16 Subroutine PROP

Description: PROP contains the thermodynamic property data for A-50,  $N_2O_4$ , MMH, and hydrazine necessary for calculations in the line modules. Also contained are references to the hydrogen and oxygen routines.

Usage: CALL PRØP (P, T, IPRØP, CP, VISC, RHØ, GAM, CØHD, L)

Referenced by: LINE, ISOTH, ADIAB, PIPL

External References: HPTD, HPTCP, HPTCV, HPTTC, HPTV, OPTD, OPTCP, OPTCV, OPTTC, OPTV

Common Blocks: CONS

User Inputs: None

Printed Output: None



#### A7.17 Subroutine PROPTY

Description: This routine provides an interface between property data obtained in PROP and H2OH2 with the usage in HEATEX.

Usage: CALL PROPTY (N, P, T, SV, K, CP, PR)

Referenced by: HEATEX

External References: PROP, H2OH2

Common Blocks: None

User Inputs: None

Printed Output: "COMBUSTION PRODUCTS NOT AVAILABLE FOR HEAT EXCHANGER

N =" (number)

#### A7.18 Function PTHEAT

Description: PTHEAT is the property routine obtained from National Bureau of Standards used to provide the specific heats of hydrogen in the range  $P = 1.$  to 5000 psi,  $T = 24.16$  to 5000°R.

Usage: HPTCV = PTHEAT (P, T, 2)

Referenced by: HPTCP, HPTCV

External References: None

Common Blocks: SPHEAT (defined in BLK2)

User Inputs: None

Printed Output: None

#### A7.19 Subroutine SAT

Description: SAT generates the saturation temperature of hydrogen or oxygen corresponding to an input pressure using linear interpolation of tabular data.

Usage: CALL SAT (IFLUID, PX, TSAT)

Referenced by: HEATEX

External References: BETA

Common Blocks: None

User Inputs: None

Printed Output: None

## A7.20 Subroutine THERM

Description: This routine provides all the thermodynamic data for oxygen using two-dimensional linear interpolation of data tables. Entry points are employed for each of the various functions requested. Data source: NBS. Linear extrapolation or ideal gas equations are used as appropriate for entries exceeding the range of tabular data.

Usage:  $CV = \emptyset PTCV(P,T)$  (see documentation in listing)

Referenced by: PROP, PREG

External References: None

Common Blocks: TPCB (data blocks TPOCB1, TPOCB2)

User Inputs: None

Printed Output:

- 1) "PRESSURE IS OUT OF RANGE" (value)
- 2) "TEMPERATURE IS OUT OF RANGE" (value)
- 3) "DENSITY IF OUT OF RANGE" (value)

followed by

- 4) "EVALUATE AT" (value)
- 5) "DENSITY COMPUTED FROM IDEAL GAS EQUATION PTD ="  
(3 values)

#### A7.21 Data Block TPOCB1

Description: TPOCB1 is a DATA BLOCK used for the oxygen thermodynamic property Subroutine THERM. (see subroutine listing)

Usage: Data loaded by system

Common Blocks: TPCB

User Input: ilone

Printed Output: None

#### A7.22 Data Block TPOCB2

Description: TPOCB2 is a DATA BLOCK used for the oxygen thermodynamic property Subroutine THERM. (see subroutine listing)

Usage: Data loaded by system

Common Blocks: TPCB

User Inputs: None

Printed Output: None

# APPENDIX B Program Input Variables

Input Name	(Dim)	Type	Primary Usage	Eng'ing Symbol	Units	Ref. Sect.	Value (Min, Nom*, Max)	Description**
ACHØKE	(10)	R	CHOKE	$A_c$	$\text{in}^2$	4.3	(0, , -)	(S)Choked exit effective flow area
AEFTUR	(5)	R	TURB	$A_T$	$\text{in}^2$	4.8	(0, .5, -)	(S)Turbine inlet effective choking area
ALPHA	(70)	R	PIPL	$\alpha$	deg.	4.1	(0, 0, 90)	Line angle with horizontal
AREAT	(10)	R	CHAM	$A_t$	$\text{in}^2$	4.7	(0, -, -)	(S)Thrust chamber effective flow area
ARFLA	(5)	R	HEATEX	A	$\text{in}^2$	4.10	(0, 2, -)	Heat exchanger flow area of side A (outside)
ARFLB	(5)	R	HEATEX	A	$\text{in}^2$	4.10	(0, 1, -)	Heat exchanger flow area of side B (inside)
AR1NJ1	(10)	R	CHAM	$A_{inj1}$	$\text{in}^2$	4.7	(0, -, -)	(S)Injector 1 flow area
AR1NJ2	(10)	R	CHAM	$A_{inj2}$	$\text{in}^2$	4.7	(0, -, -)	(S)Injector 2 flow area
AVENT	(10)	R	TANK	$A_v$	$\text{in}^2$	4.4	(0, .2, -)	Tank vent valve flow area
CDAV	(30)	R	VALVG/L	$C_d A$	$\text{in}^2$	4.5	(0, , -)	(S)Valve effective flow area
CDC1	(10)	R	CHAM	$C_{Dinj1}$	-	4.7	(0, .6, 1.)	Injector 1 flow coefficient
CDC2	(10)	R	CHAM	$C_{Dinj2}$	-	4.7	(0, .6, 1.)	Injector 2 flow coefficient
CEF1	(5)	R	TURB	$a_1$	-	4.8	(0, , -)	Turbine efficiency curve coefficient
CEF2	(5)	R	TURB	$a_2$	-	4.8	(-, ,0)	Turbine efficiency curve coefficient
CHAMMR	(10)	R	CHAM	$MR_D$	-	4.7	(0, 0., -)	(C)Chamber required mixture ratio (constraint)

\*Underlined value indicates default value if no user input. If not so indicated, default value is zero which is acceptable in most cases.

\*\*Permissible state variables preceded by (S), optional design constraints preceded by (c).

APPENDIX B Program Input Variables (Continued)

Input Name	(DIM)	Type	Primary Usage	Eng'ng Symbol	Units	Ref. Sect.	Value (Min, Nom*, Max)	Description
CP	(70)	R	LINE	$C_p$	B/lbm °R	4.1	1.	Gas specific heat (const. p) (normally internal)
CP1	(10)	R	TANK	$C_{p1}$	B/lbm °R	4.4	(0, 3, -)	Tank species 1 (initial) specific heat
CP2	(10)	R	TANK	$C_{p2}$	B/lbm °R	4.4	(0, 0, -)	Tank species 2 (optional) specific heat
DELT	-	R	TANK	$\Delta t$	sec	4.4	(0, 1, -)	Time increment for TANK integration
DHYA	(5)	R	HEATEX	$D_h$	in	4.10	(0, 2, -)	Heat exchanger hydraulic diameter, side A
DHYB	(5)	R	HEATEX	$D_h$	in	4.10	(0, 1, -)	Heat exchanger hydraulic diameter, side B
DIAD	(5)	R	PUMP	$D_{design}$	in	4.9	(0, 9, -)	Pump diam. - reference design
DIALI	(70)	R	LINES	D	in	4.1	(0, 1, -)	(S)Line inside diameter
DIAT	(5)	R	TURB	$D_T$	in	4.8	(0, 9, -)	(S)Turbine rotor tip diameter
DISØC	(10)	R	CHAM	-	-	4.7	(.4, .8, 1.)	Fraction $NH_3$ dissociated - $H_2H_4$ Monopropellant
DPLINE	(70)	R	LINE	$\Delta P_D$	psi	4.1	(0, 0., -)	(C)Line required pressure drop (constraint)
DPPUMP	(5)	R	PUMP	$\Delta P_D$	psi	4.9	(0, 0., -)	(C)Pump required pressure rise (constraint)
DPVALV	(30)	R	VALVG/L	$\Delta P_D$	psi	4.5	(0, 0., -)	(C)Valve required pressure drop (constraint)



# APPENDIX B Program Input Variables (Continued)

Input Name	(Dim)	Type	Primary Usage	Eng'ng Symbol	Units	Ref. Sect.	Value (Min., Nom*, Max)	Description
DQIN	(10)	R	TANK	$\dot{Q}$	B/sec	4.4	(0, 0, -)	Tank heat input
DY LIM	-	R	NLSOLV	$\Delta y_{\max}$	-	3.5	(.01, <u>.1</u> , 1.)	Maximum change in each Y during an iteration
DYUP	-	R	NLSOLV	$\Delta \tilde{y}$	-	3.5	(0, <u>.3</u> , 100)	Change in $Y_i$ yielding partial derivative updates $dz_j/dy_i$
ECF	(10)	R	CHAM	$\epsilon_{C_F}$	-	4.7	(0, <u>.98</u> , 1.)	Thrust coefficient efficiency
ECSTAR	(10)	R	CHAM	$\epsilon_{C^*}$	-	4.7	(0, <u>.98</u> , 1.)	C-star efficiency
EMIS	(70)	R	PIPL	$\epsilon$	-	4.1	(0, <u>.5</u> , 1.)	Emissivity
EPSDY	-	R	NLSOLV	$\epsilon_{\Delta y}$	-	3.5	( $10^{-8}$ , <u><math>10^{-6}</math></u> , $10^{-4}$ )	Convergence criteria on each state variable
EPSZ	-	R	NLSOLV	$\epsilon_f$	-	3.5	( $10^{-8}$ , <u><math>10^{-6}</math></u> , $10^{-4}$ )	Convergence criteria on constraint vector norm
ERATIO	(10)	R	CHAM	$\epsilon$	-	4.7	(1, <u>40</u> , -)	(S)Nozzle expansion ratio requirement
FD	(5)	R	HEATEX	-	-	4.10	(0., <u>0.</u> , 1.)	HX flag (>0.) for optional input (2/3): HEWPA, ARFLA, DHYA and side B
FN	(5)	R	HEATEX	-	-		( , <u>.98</u> , 1.)	Crossflow correlation factor
GEE	-	R	PIPL	g	ft/sec <sup>2</sup>	4.1	(0, <u><math>10^{-8}</math></u> , -)	Local acceleration
GR	(5)	R	PUMP	$R_G$	-	4.9	(0, 1, -)	(S)Gear ratio : $N_{\text{turb}}/N_{\text{pump}}$
HEWPA	(5)	R	HEATEX	-	in	4.10	(0, 4, -)	Heat exchanger wetted perimeter of flow passage A (outside)

APPENDIX B Program Input Variables (Continued)

Input Name	(Dim)	Type	Primary Usage	Eng'ing Symbol	Units	Ref. Sect.	Value (Min., Nom*, Max)	Description
HEWPB	(5)	R	HEATEX	-	in	4.10	(0, 1, -)	Heat exchanger wetted perimeter of flow passage B (inside)
HNPR	-	R	PIPL	-	-	4.1	(0, .4, -)	Heat transfer coefficient exponent
HNRE	-	R	PIPL	-	-	4.1	(0, .8, -)	Heat transfer coefficient exponent
HR	(70)	R	PIPL	-	in	-	(0, 0, -)	Hydraulic radius of liquid line - optional replacing DIALI
HTAREA	(5)	R	HEATEX	-	in <sup>2</sup>	4.10	(0, 100, -)	Heat exchanger total heat transfer surface area
HXCFLØ	(5)	I	HEATX	-	-	4.10	(0, 0, 1)	Heat exchanger - cross flow type indicator. Otherwise parallel flow
HXRFLØ	(5)	I	HEATX	-	-	4.10	(0, 0, 1)	Heat exchanger - reverse flow type indicator. Otherwise parallel flow
ISPD	(10)	R	CHAM	I <sub>SPD</sub>	sec	4.7	(0, 300, -)	(C)Design requirement specific impulse
ITURB	(5)	I	PUMP	-	-	4.9	(1, 1, 5)	Number of turbine driving pump
KA	(70)	R	LINE	γ	-	4.1	(1+, 1.2, 1.6)	Gas specific heat ratio (normally internal)
KTENV	-	R	PIPL	-	B/ft-hr °R	4.1	(0, .01, -)	Conductivity of environment
KTHER	(70)	R	LINE	K	B/ft-hr °F	4.1	.2	Fluid thermal conductivity (normally internal)
LAMDA	(10)	R	CHAM	λ	-	4.7	(0, .98, 1.)	Nozzle divergence loss factor
LCHAT	(10)	I	CHAM	-	-	4.7	(1, 1, 70)	Number of line at injector 1 inlet

# APPENDIX B Program Input Variables (Continued)

Input Name	(Dim)	Type	Primary Usage	Eng'ng Symbol	Units	Ref. Sect.	Value (Min, Nom*, Max)	Description
LCHA2	(10)	I	CHAM	-	-	4.7	(0, 2, 70)	Number of line at injector 2 inlet
LCHAM	(10)	I	CHAM	-	-	4.7	(0, 3, 70)	Number of line at chamber (GG) outlet. None for thruster
LCHØKE	(10)	I	CHOKE	-	-	4.3	(1, 1, 70)	Number of line at CHOKE inlet
LDMI	(10)	I	HEATX	-	-	4.4	(0, 1, 70)	Number of gas line inlet to tank
LDMØ	(10)	I	HEATX	-	-	4.4	(0, 2, 70)	Number of gas line outlet from tank
LDWI	(10)	I	HEATX	-	-	4.4	(0, 3, 70)	Number of liquid line inlet to tank
LDWØ	(10)	I	HEATX	-	-	4.4	(0, 4, 70)	Number of liquid line outlet from tank
LENGTH	(5)	R	HEATEX	L <sub>HX</sub>	in	4.10	(0, 100, -)	(S)Heat exchanger tube length
LFB	(20)	I	FEEDB	-	-	3.4	(1, 1, 70)	Number of line beginning feedback loop
LHXAI	(5)	I	HEATX	-	-	4.10	(1, 1, 70)	Number of line at heat exchanger side A inlet
LHXAØ	(5)	I	HEATX	-	-	4.10	(1, 2, 70)	Number of line at heat exchanger side A outlet
LHXB1	(5)	I	HEATX	-	-	4.10	(1, 3, 70)	Number of line at heat exchanger side b inlet
LHXBØ	(5)	I	HEATX	-	-	4.10	(1, 4, 70)	Number of line at heat exchanger side B outlet
LIJU1	(5)	I	JUNCL	-	-	4.2	(0, 1, 70)	Line number at inlet of junction 1
LIJU2	(5)	I	JUNCL	-	-	4.2	(0, -, 70)	Line number at inlet of junction 2
⋮								
LIJU10	(5)	I	JUNCL	-	-	4.2	(0, -, 70)	Line number at inlet of junction 10

APPENDIX B Program Input Variables (Continued)

Input Name	(Dim)	Type	Primary Usage	Eng'ng Symbol	Units	Ref. Sect.	Value (Min, Nom*, Max)	Description
L0JU1	(5)	I	JUNCL	-	-	4.2	(0, 2, 70)	Line number at outlet of junction 1
...								
L0JU10	(5)	I	JUNCL	-	-	4.2	(0, -, 70)	Line number at outlet of junction 10
LPRI	(10)	I	PREG	-	-	4.6	(1, 1, 70)	Number of line at pressure regulator inlet
LPR0	(10)	I	PREG	-	-	4.6	(1, 2, 70)	Number of line at pressure regulator outlet
LPUMPI	(5)	I	PUMP	-	-	4.9	(1, 1, 70)	Number of line at pump inlet
LPUMP0	(5)	I	PUMP	-	-	4.9	(1, 2, 70)	Number of line at pump outlet
LTURBI	(5)	I	TURB	-	-	4.8	(1, 1, 70)	Number of line at turbine inlet
LTURB0	(5)	I	TURB	-	-	4.8	(1, 2, 70)	Number of line at turbine outlet
LTYPE	(70)	I	LINE	-	-	-	(1, <u>4</u> , 4)	Line type: 1 = PIPL, 2 = ADIAB 3 = ISOTH, 4 = Ideal
LVAI	(30)	I	VALVG/L	-	-	4.5	(1, 1, 70)	Number of line at valve inlet
LVA0	(30)	I	VALVG/L	-	-	4.5	(1, 2, 70)	Number of line at valve outlet
MAXIT	-	I	NLSOLV	-	-	3.5	(1, <u>40</u> , 100)	Maximum iterations of NLSOLV
NODEL	(70)	I	PIPL	-	-	4.1	(1, <u>3</u> , 20)	Number of nodes in line
NPLINE	(70)	I	PR0PTY	-	-	-	(1, 3, 10)	Number of propellant in line $\pm 1=H_2$ , $\pm 2=O_2$ , -3=A-50, -4=N <sub>2</sub> O <sub>4</sub> , -5=MMH, -6=N <sub>2</sub> H <sub>4</sub> , etc.

# APPENDIX B Program Input Variables (Continued)

Input Name	(Dim)	Type	Primary Usage	Eng'ng Symbol	Units	Ref. Sect.	Value (Min, Nom*, Max)	Description
NPRENV	-	R	PIPL	$N_{PR_E}$	-	4.1	(0, <u>.6</u> , 1)	Prandtl number of environment
NSTATE	-	I	NSOLV	n	-	3.5	(0, ~ 15, 40)	Number of state variables and constraints
PATM	-	R	CHAM	$P_{atm}$	psi	4.7	(0, <u><math>2 \times 10^{-8}</math></u> , -)	Atmospheric pressure
PCD	(10)	R	CHAM	$P_{CD}$	psi	4.7	(0, 400, -)	Design requirement chamber pressure
PG1	(70)	R	LINE	$P_i$	psi	4.1	800	(S)Line inlet pressure
PG2	(70)	R	LINE	$P_o$	psi	4.1	800	Line outlet pressure
PGPBL	(70)	R	LINE	$P_{oD}$	psi	4.1	(0, 800, -)	(C)Required line outlet pressure
PGT1	(70)	R	LINE	$P_{ti}$	psi	4.1	800	Line inlet total pressure
PGT2	(70)	R	LINE	$P_{to}$	psi	4.1	800	Line outlet total pressure
PL0S	(70)	R	PIPL	-	-	-	(0, 0, -)	Pressure loss coefficient
PØW0	(5)	R	PUMP	$b_o$	-	4.9		Pump performance characterization Required input power versus flow rate at design speed. $IP = b_o + b_1\dot{w} + b_2\dot{w}^2 + b_3\dot{w}^3$ $IP = \text{ft-lbf/sec}, \dot{w} = \text{lbm/sec}$
PØW1	(5)	R	PUMP	$b_1$	-	4.9		
PØW2	(5)	R	PUMP	$b_2$	-	4.9		
PØW3	(5)	R	PUMP	$b_3$	-	4.9		
PØWT	(5)	R	TURB	IP	ft-lbf/sec	4.8	(0, -, -)	(S)Turbine shaft power output - input power to pump
PRE	(10)	R	PREG	$P_{reg}$	psi	4.6	(0, 400, -)	(S)Regulator outlet pressure

# APPENDIX B Program Input Variables (Continued)

Input Name	(Dim)	Type	Primary Usage	Eng'ing Symbol	Units	Ref. Sect.	Value (Min, Nom*, Max)	Description
PTURBØ	(15)	R	TURB	$P_{T0}$	psi	4.8	(0, 14, -)	(S)Turbine duct back pressure if no duct, $P_{to} = P_{atm}$
PTANK	(10)	R	TANK	$P_{tank}$	psi	4.4	(0, 800, -)	(S)Tank initial pressure
PVENT	(10)	R	TANK	$P_{vent}$	psi	4.4	(0, 1,000, -)	Tank valve vent pressure
PW0	(5)	R	PUMP	$a_0$	-	4.9	Pump performance characterization. Pressure rise versus flow rate at design speed. $\Delta P = a_0 + a_1 \dot{w} + a_2 \dot{w}^2$ $\Delta P = \text{psi} \quad \dot{w} = \text{lbm/sec}$	
PW1	(5)	R	PUMP	$a_1$	-	4.9		
PW2	(5)	R	PUMP	$a_2$	-	4.9		
R1	(10)	R	TANK	$R_1$	$\frac{\text{ft-lbf}}{\text{lbm}^\circ\text{R}}$	4.4	(0, 770, -)	Tank species 1 (initial) gas constant
R2	(10)	R	TANK	$R_2$	$\frac{\text{ft-lbf}}{\text{lbm}^\circ\text{R}}$	4.4	(0, 0, -)	Tank species 2 (optional) gas constant
RDPUMP	(5)	R	PUMP	$R_N$	-	4.9	(0, 1, ~ 10)	(S)Actual/Ref Pump diameter ratio
RFLAG	-	R	ALL	-	-	-	(0, <u>1</u> , -)	Print flag, # complete prints
RHO2	(70)	R	LINE	$\rho$	lbm/ft <sup>3</sup>	4.1	60	Fluid density at line outlet (normally internal)
RHOE	-	R	PIPL	$\rho_E$	lbm/ft <sup>3</sup>	4.1	(0, <u><math>1.15 \times 10^{-7}</math></u> , -)	Density of environment
RI	(5)	R	HEATEX	$R_i$	in	4.10	(0, 1, -)	(S)Heat exchanger inside tube radius
RØ	(5)	R	HEATEX	$R_o$	in	4.10	(0, 2, -)	(S)Heat exchanger outside tube radius
RPMD	(5)	R	PUMP	$N_D$	RPM	4.9	(0, 50k, -)	Pump designed operating speed
RPMT	(5)	R	TURB	$N_T$	RPM	4.8	(0, 50k, -)	(S)Turbine rotational speed

# APPENDIX B Program Variables (Continued)

Input Name	(Dim)	Type	Primary Usage	Eng'ing Symbol	Units	Ref. Sect.	Value (Min, Nom*, Max)	Description
STATE	(2,40)	I	PREPRC	-	-	3.2	e.g., WDOT, 3	State variable specifications (variable name, ID number)
SYSKOM	(2,150)	I	PREPRC	-	-	3.1	e.g., LINE, 3	System component specifications
TEMP1	(70)	R	LINE	T <sub>i</sub>	°R	4.1	460	(S)Line inlet temperature
TEMP2	(70)	R	LINE	T <sub>o</sub>	°R	4.1	460	Line outlet temperature
TENV	-	R	PIPL	T <sub>E</sub>	°R	4.1	(0, 460, -)	Temperature of environment
TH	(70)	R	PIPL	th	in	4.1	(0, .02, -)	Line wall thickness
THECA	(5)	R	HEATX	T <sub>HXA</sub>	°R	4.10	(0, 400, -)	(C)Heat exchanger outlet temperature constraint - side A (outside)
THECB	(5)	R	HEATX	T <sub>HXB</sub>	°R	4.10	(0, 400, -)	(C)Heat exchanger outlet temperature constraint - side B (inside)
THICK	(5)	R	HEATEX	th	in	4.10	(0, .020, -)	Heat exchanger inside tube wall thickness
THRTD	(10)	R	CHAM	F <sub>D</sub>	lb <sub>f</sub>	4.7	(0, 1000, -)	(C)Design requirement thrust
TIME	-	R	SSPIPE	t	sec	-	(0, 0, -)	Integration time for TANK integration
TIMEHD	-	R	SSPIPE	-	sec	-	(0, 0, -)	Stop time for TANK integration
TLIQ	(10)	R	TANK	T <sub>liq</sub>	°R	4.4	(0, 460., -)	Tank temperature of liquid
TTANK	(10)	R	TANK	T <sub>tank</sub>	°R	4.4	(0, 460., -)	Tank initial temperature
TTEMP1	(70)	R	LINE	T <sub>ti</sub>	°R	4.1	460	Line inlet total temperature

APPENDIX B Program Input Variables (Continued)

Input Name	(Dim)	Type	Primary Usage	Eng'ng Symbol	Units	Ref. Sect.	Value (Min, Nom*, Max)	Description
TTEMP2	(70)	R	LINE	$T_{to}$	°R	4.1	460	Line outlet total temperature
VISC	(70)	R	LINE	$\mu$	lbm/ft-sec	4.1	$10^{-5}$	Fluid Viscosity (normally internal)
WISE	-	R	PIPL	$\mu_E$	lbm/ft-sec	4.1	(0, $8.5 \times 10^{-6}$ , -)	Viscosity of environment
VTANK	(10)	R	TANK	$V_t$	ft <sup>3</sup>	4.4	(0, 100., -)	Tank total volume
WDOT	(70)	R	LINE	$\dot{W}$	lbm/sec	4.1	(0, -, -)	(S) Mass flow rate in line (negative for checked flow)
WOL	(10)	R	TANK	W	lbm	4.4	(0, 0, -)	Tank initial weight of liquid
WTHCON	(70)	R	PIPL	$K_W$	B/ft-hr-°R	4.1	(0, <u>10</u> , -)	Wall thermal conductivity
X	(40)	R	NLSOLV	X	as required	3.5	normally, blank	State variable values corresponding to names in array STATE
XA	(5)	R	HEATEX	$X_A$	-	4.10	(0., 1., 1.)	Heat exchanger fluid quality - side A inlet: 0. = liquid, 1. = gas
XB	(5)	R	HEATEX	$X_B$	-	4.10	(0., 0., 1.)	Heat exchanger fluid quantity - side B inlet: 0. = liquid, 1. = gas
XLENG	(70)	R	LINES	L	ft	4.1	(0, 50, -)	(S) Line length
XREF	(40)	R	NLSOLV	$X_{ref}$	as required	3.5	normally, blank	Normalizing values of X. If blank, XREF(I) = X(I) as input
YBNDL	(40)	R	NLSOLV	$y_{min}$	-	3.5	(-10, <u>-10</u> , ~ .5)	Lower limit on normalized state variables
YBNDU	(40)	R	NLSOLV	$y_{max}$	-	3.5	(.5, <u>10</u> , 10)	Upper limit on normalized state variables



## APPENDIX C Deck Setup

▽ RUN

▽ ASG A = xxxxx

ACPS PROGRAM TAPE

▽ ASG B

PREPRC/SSPIPE INTERFACE

▽ XQT CUR

TRW A

IN A

TRI A

TØC

▽ XQT PREPRC

Program data I must include SYSCØM = (list of all component module names and ID numbers), STATE = (list of all state variable names and ID numbers), and state variable initial estimates. May also contain comment cards, component connections, component specifications, boundary conditions, design constraints, and equation solver control data.

ENDCAS

▽ FØR,B GATHER,GATHER

▽ XQT SSPICE,SSPIPE

Program data II must contain all necessary data not loaded under execution of PREPRC above. May change any input values except SYSCOM, STATE, and initial estimate of state variables.

ENDCAS

An alternate deck setup is possible if, for some previous execution, the card ▽ ASG B was replaced with ▽W ASG B = SAVE, and the resulting output tape was saved. In this case, the deck setup is simplified to:

```

▽ RUN
▽ ASG A = xxxxx          ACPS PROGRAM TAPE
▽ ASG B = xxxxx          PREPRC/SSPIPE INTERFACE
▽ XQT CUR
  TRW A
  IN  A
  TRI A
  TØC
▽ FØR,B GATHER,GATHER
▽ XQT SSPICE, SSPICE
    Program data (same as Program data II above)
ENDCAS

```